SASKATCHEWAN RESEARCH COUNCIL

# A REVIEW OF THE FACTORS AFFECTING PESTICIDE SPRAY DRIFT

by

J. Maybank

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# PREFACE

This report, addressed to Agriculture Canada, was in response to a request from that Department to undertake such a review. The contract covering the work was part of the Toxic Chemical Fund Project, specifically identified as No. 7040-3 (Ref. 01862-3-004) and set out the following Scope of Work:

To provide -

1. An appraisal of the factors affecting spray drift of agricultural pesticides applied by conventional techniques by ground or air.
2. An appraisal of the parameters used to measure spray drift.
3. A protocol for pesticide registration requirements.

Include tasks -

1. Review current literature on drift, listing and assessing the factors that affect it.
2. Review and detail the parameters which must be measured when determining spray drift.
3. Develop protocols using the above two which indicate data requirements for the following:
   (a) boom, ground rig
   (b) fixed wing agricultural spray aircraft
   (c) helicopter
4. Report on above 3, including bibliography of relevant, and copies of most relevant, papers.

## SUMMARY

Pesticide spray droplets are customarily released in the atmosphere in such a manner that they move from the release point of either a ground-rig or aircraft spray vehicle to the desired surface or foliage target. In the course of this process some fraction of the droplets inevitably leaves the target area and moves off downwind. This off-target drift may be viewed as consisting of three consecutive processes, each characterized by a set of parameters affecting the drift behaviour: emission or dissemination, transport and deposition.

The dissemination stage is responsible for the initial droplet size spectrum, which in turn is a complex function of solution properties such as viscosity and surface tension and of the spray nozzle type and hydraulic pressure.

The intermediate transport or dispersal phase is controlled by release height, spray vehicle and wind speed vectors, together with vehicle-induced, and ambient, turbulence. As distance from the source increases, those aspects associated with the vehicle diminish in importance, leaving the free atmosphere effects to control the distant travel of the droplet cloud. A vital property of the droplets themselves will be whether any of the spray solution components are volatile; if the carrier liquid is water, its evaporation within a few tens of seconds after dissemination will considerably alter the droplet spectrum and hence droplet fall speeds. In such circumstances two other atmospheric parameters assume importance, viz temperature and relative humidity.

Finally, deposition onto the ground or onto plant surfaces will come into play. The nature of these surfaces, the state of the evaporated droplets and the wind profile and turbulence near the ground are the factors of concern here.

Clearly, spray drift is a complex function of a variety of factors, each of which must be separately measured and its role independently assessed. To set safe limits on spraying requires as well two further aspects to be identified and assessed: (i) how much pesticide can be accepted as tolerable in the off-target environment, given the nature of susceptible biota there; and (ii) what loss in target coverage can be accepted as a trade-off for reduced off-target drift? With the answers to these aspects given, drift limits can be set and the equipment and spray vehicle parameters required to meet these limits determined.

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# A REVIEW OF THE FACTORS AFFECTING PESTICIDE SPRAY DRIFT

## 1. INTRODUCTION

Herbicides, insecticides and other pesticides are used routinely in farming to control pests that, if left uncontrolled, would have detrimental effects on agricultural yield, and hence on economic return to the farmer. In almost all cases these pesticides are applied in the form of a spray of fine droplets that is emitted from some spray vehicle moving over the target area. It is naturally intended that all such droplets will move in the air from the point of emission to the target soil or foliage, and that, following deposition, the active chemical component (the pesticide) will begin its control action.

However, from each spray operation, some pesticide material is known to escape the target area and to move off downwind, and the detection of various pesticides in non-target areas clearly confirms this. Both vapour and droplet drift may occur. The former is a problem with volatile pesticides, and typically commences after the droplets are deposited within the target area. Such vapour loss may take place over days or even weeks after the spray operation. It is independent of the spray system and vehicle used, and is a function primarily of the vapour pressure of the chemical and of the temperature of the surface on which the droplets initially deposit. As such, vapour drift lies outside the scope of the present review. On the other hand, droplet, or spray, drift occurs at the time of the actual spray operation and its magnitude is closely related to the spray system being used. Subsequent behaviour of the drifting droplets then depends on a complex interaction of two primary factors,

viz, droplet size and air motion, plus a number of lesser and inter-dependent parameters. This report addresses these various factors in terms of what is presently known about them and how they should be measured and assessed for relative importance. The resultant understanding of drift processes should then lead naturally to determining recommended procedures and operational limits for various pesticide and spray equipment combinations.

For the setting of pesticide protocols and registration requirements, two other major inputs are vital, but which will not be directly addressed in this report. The first is the consideration that the very reason for pesticide spraying is pest control, and that this places essential conditions on target and droplet size interaction. The pattern of droplet deposit in the test area (either on the soil or foliage) and its degree of uniformity must be appropriate to the effect desired. Any worsening of pattern uniformity to gain spray drift reduction may well be counter-productive. This has frequently happened for herbicide spray applications, where a drift reduction gained through some modification of technique (e.g. a lower boom) leads to unacceptably poor (to the farmer at least) weed control in the field. In such circumstances he might simply increase the application rate of the chemical, thereby negating the improvement in drift control. The same thing can happen with insecticides where, in an attempt to lessen drift by reducing the numbers of small droplets emitted, one might be removing the most effective droplet size from the target foliage. Trade-offs may well be necessary between maximum target effectiveness per unit mass of chemical and minimum off-target spray drift, but clearly, it is essential to identify such trade-

offs and to establish whether they are warranted.

The second essential input concerns the pesticide chemical itself. In order to set application procedures appropriate for a desired limit for spray drift, it is necessary to have information on the biological action of the pesticide being used and of its potential hazard to susceptible biota downwind of the target area. With this knowledge, some level of environmental contamination which is acceptable in certain situations can be established, which in turn sets the limit on spray drift for that off-target situation.

## 2. FACTORS AFFECTING SPRAY DRIFT

There is a complex mix of factors that govern spray drift behaviour, starting from the dissemination stage at the nozzles and leading, after transport and diffusion in the atmosphere, to deposition on off-target surfaces downwind. Research to date has addressed various combinations of these stages and factors, but seldom have all aspects been investigated in a single experiment or theoretical analysis. The entire process is just too complicated for a comprehensive treatment, so restrictions and simplifying assumptions have to be made.

As stated in the previous section, the two primary factors may be considered to be the droplet and air motions relative to each other. The former is a function of droplet size. For each diameter, it is possible to calculate a terminal velocity, which in still air, and for a droplet starting from rest, permits a determination of settling time from any release height. If the droplets were all of the same size and the ambient windspeed constant in both space and time, the downwind

resting place of the emitted spray could be easily found. There would be, in such circumstances, no distinction possible between "target" and "off-target" deposits: the entire spray would come out as a single deposit band. Its width would be relatively narrow, being set by the length of the spray boom nozzle array, and by whatever variations might occur in release height or initial droplet trajectory.

Even for a heterogeneous droplet spray, the problem would not be very difficult to handle in a uniform air flow, if only the droplet size spectrum were known and truly controllable. Then, each size interval (which could be set as acceptably narrow as desired) could be assigned the appropriate terminal velocity and the position on the ground of each size of droplets calculated. Knowing the fraction of the spray solution contained in each size-range interval, the deposit density would be found as a function of downwind distance by adding the contributions for each droplet size group. Unfortunately, of course, the variations in wind-speeds, together with naturally-occurring air turbulence variations, make it impossible to obtain realistic deposit data from this simplistic approach.

The problem of predicting successfully a downwind drift pattern actually arises even before air motions come into play, for the droplet spectrum is itself a complex and frequently varying product of several factors right at the spray vehicle. The most common type of nozzle presently used in both groundrig and aircraft application consists of a metal tip or plug having a small orifice hole machined into it. Through this opening the spray solution is forced under pressure. It then spreads out as an unstable sheet or cone of fluid, followed in short order (of a

few milliseconds or so) by breakup into filaments and then into droplets. This dissemination process is affected by such properties of the pesticide solution as viscosity and surface tension, together with the emission pressure on the fluid, and the dimensions of the orifice as well as its configuration. Increased values for the first two will tend towards retarding the liquid break-up, thereby increasing the droplet sizes. Also, a larger orifice opening will generally result in a coarser spray at the same hydraulic pressure than would a smaller one. On the other hand, breakup is increased and a finer drop spectrum ensues when the pressure is increased. However, the relationship is extremely complex, and in practice it is impossible to predict the drop spectrum to be expected from any combination of these four factors (viscosity, surface tension, pressure and orifice diameter). This is especially true for the small droplet end of the size curve, which is after all the most critical portion for the spray drift problem. Here, both the magnitude and shape of the curve may be determined primarily by small irregularities on the edges of the orifice opening rather than by the action of the other factors.

There are several other nozzle designs presently in use besides the flat fan and cone ones, but which may also be characterized as "passive" or static types, with the fluid flow being forced through them by some impressed pressure (or even just by gravity). Their flow rates and droplet size patterns will therefore depend on the same factors as the flat-fan ones do, though perhaps to a different degree. On the other hand, several new approaches utilize an "active" or dynamic nozzle design in which the nozzle interacts with the fluid flow to enhance breakup and droplet formation. These commonly take the form of a rapidly spinning

disc or cone, onto the surface of which the solution is fed at relatively low pressure. Centrifugal forces effect the breakup of the fluid sheet as it reaches (or extends beyond) the periphery of the rotor. In principle, this type of atomizer should produce homogenous droplets, or at least a relatively narrow droplet spectrum, with the size dependent, in a predictable manner, on surface tension of the fluid, rotor diameter and rotational speed. In practice, the equation holds only for very low fluid flowrates. At higher values, breakup occurs not at the rotor edge but at some fluid periphery of varying diameter, resulting in a heterogeneous droplet spray (but one with a distinctly narrower size range nevertheless, than those produced by static nozzles). The size spectrum is no longer independent of solution viscosity, but remains independent of hydraulic pressure and fluid feed rate, over quite a wide range at least.

Before considering the various transport and dispersal factors, it is important to note that neither the droplet pattern nor the initial size spectrum is independent of the forward motion of the vehicle from which the spray is being emitted. At aircraft speeds breakup of the fluid sheets and filaments is significantly altered towards smaller sizes by the air flow past the nozzles. The emission pattern too is affected, a situation that commonly varies nozzle by nozzle according to the changing turbulence along the wings. The much lower speed of groundrig spray vehicles does not produce much effect on droplet pattern or spectrum by itself, but boom and wheel bounce due to rough terrain affect both features in a most erratic manner.

Following dissemination, the emitted droplets spread out from the nozzle and commence their descent towards the ground. Their initial

trajectories and emission velocities are quickly superseded by the airflow, which initially is a vector combination of the ambient wind speed and the spray vehicle velocity. The effective release height is commonly determined by where this flow change occurs. For a groundrig, the point lies close to the nozzle outlet, and so boom height becomes the useful measure of this parameter. For fixed-wing aircraft, wing tip vortex is a major input into the initial condition of the spray droplet cloud, and sets an effective release height that may be several times the nozzle-to-ground distance. The same is true for helicopters where it is the rotor vortex. In both cases, while a mean release height may be observed, and in some cases predicted, on the basis of aircraft weight, speed and wing loading, variation about it for individual droplets can be considerable. This feature plays a major role in spreading the initial spray drift and in causing large variations in off-target deposition close in to the sprayed area (i.e. relatively short downwind distances).

One factor, frequently varied to enhance droplet breakup or to improve the target deposit pattern, is the emission angle of the spray. When tried with aircraft, the breakup pattern (in which the aircraft speed would play a greater role) may be altered towards a somewhat narrower droplet spectrum; however, the fraction of small, drift-prone droplets tends to be increased with little improvement in target deposit uniformity being achieved. In groundrig applications, emission angles diverging from the normal vertical downward position, really alter only the effective release height, shifting it upwards. The target pattern can be made more uniform that way, in some cases, but at the expense of increasing the spray drift. In any case, spray release angle appears to

be only a minor factor in nearly all application systems.

A much more significant factor is the rapid evaporation of the water carrier of the spray solution (or indeed the volatility of any major component). In typical operations, between 90 and 99% of the spray volume will be water, and this will evaporate very quickly under the air temperature and humidity conditions typical of spraying activity (e.g. 10-25°C and 30-70% relative humidity). Depending on actual values for these two controlling parameters, a 100μ diameter solution droplet initially containing 98% water, say, will diminish in size to around 30μ in a very few seconds.

For a 500μ droplet from the same spray solution, the time is considerably longer, typically several minutes. In both cases, the result is usually a still-liquid droplet composed mostly of the pesticide plus involatile additives and a few percent residual water. The larger droplets in any spray will commonly reach the ground, i.e. deposit out in the target area, before evaporation is complete; indeed the drop size spectrum of the swath deposit may not differ much from the initial one at the nozzle. On the other hand, the smaller droplets of 100μ or less may reach their final sizes before deposition occurs.

Thus, the initial drift situation is quite complex, entailing a cloud of droplets possessing a variety of initial velocities impressed at the nozzle, together with vertical motions produced by vehicle turbulence and horizontal ones influenced by the vehicle speed and by the ambient air movement. Fortunately this period is short-lived, and by the time the downwind drift motion is impressed on the cloud by the windspeed, the sprayer-impressed factors are beginning to lose their

importance. After a relatively short period, of roughly 10 to 30 seconds, the spray drift cloud will consist of droplet sizes determined by the involatile fraction (i.e. "dry" droplets) in the solution, with terminal velocities appropriate to these sizes, moving with the ambient wind and subject to the relevant turbulence structure of the air. One residual factor impressed on the spray by the vehicle will be the release height and the wide variation in it that would be the case for aircraft and helicopter application, due to the vortex effect. This assumes an important role in spray drift modelling, at least for the early part of the droplet cloud's downwind movement.

Atmospheric turbulence imparts to the droplets a rapidly varying vertical velocity that may impel them upwards as well as down. The scale size of the eddies will vary considerably, giving both time and distance factors to be considered. Variations in the instantaneous horizontal windspeed (and direction) are also an integral part of the total structure.

The effect that this turbulence structure has on the diffusion and downwind travel of small particles or droplets moving in the airflow has been successfully modelled for a variety of circumstances and simplifying assumptions. It is customary to treat the problem on the basis of a relatively small number of stability classes, ranging from a very stable to a very unstable atmosphere. The former prevails overnight and into the earliest portion of morning hours, while the latter is typical of mid-afternoon conditions on warm, sunny days. Each of these stability extremes produces a distinctly different turbulence regime, with resulting differences in droplet drift distances and deposit patterns. Under very stable conditions, the spray tends to move out of the target area

as a fairly uniform airborne layer, and with upward diffusion being suppressed, the droplet concentration within the drift cloud tends to remain high. Fall-out rates are high and so at relatively short off-target distances, deposition will be a sizable fraction of the total airborne cloud. With very unstable conditions prevailing, vertical diffusion will occur; the droplet concentration will decrease more rapidly with increasing downwind distance, but the rate of deposition will be reduced. In both cases, the amount of initial off-target drift, dependent on droplet size, release height, and horizontal windspeed (plus the vortex effects if aircraft are used) might well be the same.

Once the drifting droplet reaches close to the foliage or ground surface, the deposition stage may be considered to have been reached. It is particularly difficult to identify and assess the various factors here, as leaf and stem diameters, leaf orientation to the wind, foliage density, etc., all become potentially important to the final motion and deposit point for the droplets. Turbulent eddies do not end once the canopy is encountered but their time and space scales will change abruptly. Fortunately for many modelling approaches, the droplet exposure to canopy-controlled turbulence is relatively short and its effects can therefore be ignored. This is a generally satisfactory approach for deposition onto bare soil or water surfaces, or even onto low crops and pasture grasses, but is distinctly less so for tall brush, shelter belts, etc., or where the pesticide in question may have different activity levels for different portions of susceptible plants (stems vs leaves for instance).

## 3. STATUS OF PRESENT DRIFT RESEARCH WORK

It should be apparent from the large number of factors involved in the entire off-target drift process that the scientific literature on the topic would be both voluminous and fragmented. It is possible, however, to discern two broad areas of research activity, one centered on the mechanical aspects, the other on atmospheric processes. Because of the fragmented nature of the total research endeavour, it is possible to review both those areas separately and roughly in the order of the factors affecting drift, as described in the previous section.

Research on nozzles, spray boom design, pressure settings and solution properties has been generally directed towards either improving the deposit pattern or to reducing drift. Only infrequently has it involved attempts to simultaneously assess and optimize both, or to develop realistic "trade-off's". Hence new systems or combinations of parameters have often been proposed to reduce drift which are subsequently found to have worsened the swath deposit uniformity (and vice versa). This apparent lack of research intensity or coordination in sprayer design may be contrasted with the wealth of comprehensive information on the chemistry and biological effects of various pesticides. The difference may be ascribed partly to the relative size of the companies engaged in manufacturing the equipment components (generally small and/or into other lines as well), and those making the chemicals (generally large). A second reason is very likely the absence of regulations governing equipment performance.

Nevertheless, a great many different styles of nozzle have been designed and are manufactured. Variations between them commonly relate to orifice size for different output rates. Shape of the actual opening has

been subjected to careful attention to improve the uniformity of emission, and hence of the deposit pattern on the ground. Overlap behaviour of adjacent nozzles has been investigated in conjunction with boom height and spacing to reduce gap or overdose occurrences. Most of this research has been carried out "in-house" by the various nozzle manufacturers and has led to the wide range of types presently on the market. Only rarely has the most important property of all, the initial drop size spectrum, been provided in the brochure information available to users.

More intensive work has involved the influence of hydraulic pressure, coupled with release height, in attempts to decrease the number of smaller droplets produced or their likelihood of drifting beyond the swath. It was clearly recognized that such efforts must run counter to achieving optimal deposit pattern, inasmuch as high pressures and boom height should improve this aspect, while changes in the opposite direction were indicated for drift control. Unless the two were measured for each proposed change (not usually done) effective compromises were missed. This was especially true when thickening agents, emulsifiers, etc., were added to the solution in an effort to reduce production of the smaller droplets. Once again the coarser spray, and hence lower drift, was accompanied by a major reduction in uniformity of target coverage. On the other hand, a few of these "ad hoc" approaches to the problem of reducing the small droplet fraction were promising, notably the development of the so-called "low-pressure" type of flat-fan nozzle (Maybank, Yoshida, Shewchuk and Grover, 1976). Surveys of the interactions of the factors affecting droplet size spectra at the nozzle and initial spray drift characteristics may be found in Yates, Akesson and Cowden (1974), Maybank, Yoshida and Grover (1974), and Nordby

and Skuterud (1975).

In addition to the difficulty of independently improving drift control and deposit pattern, much of the effort directed towards coarsening the spray suffered from a property common to droplet-producing devices that emit a wide range of sizes. Simply shifting the entire spectrum upward, as measured by its most commonly used characteristic, the Volume Median Diameter (VMD - that diameter dividing the entire spectrum such that 50% of the emitted volume is in smaller droplets and 50% in larger), might also result in an even more heterogeneous spray. That is, such an upward shift could occur without reducing the fraction of the volume being emitted as fine droplets. More seriously, it could reduce the volume of spray solution being emitted in the droplet sizes considered to be most effective for biological control.

This aspect of effective drop size has been addressed for a variety of insect-insecticide combinations, but has been all but ignored until recently for herbicides. For the former the optimum for most species appears to be 80-150μ but might well be lower (Lawson and Uk, 1979). It is obviously going to depend on insect size, mobility, and location within a crop canopy. There is less specificity (but less research) on the range of droplet sizes that might be most effective for weed control in an agricultural setting. Most evidence to date indicates that 200-300μ droplets are likely to provide the most efficient control per unit mass of herbicide, but the limits of this range are not well-identified and might vary with weed size and mode of herbicide action (Lake, 1977; Ayres and Merritt, 1978). Nevertheless, this range has clearly been identified as acceptable in the development of controlled droplet applicators (CDA)

and of ultra low volume (ULV, commonly considered to be around 1-10 L/ha). For both, the emphasis has been on clearly identifying the initial droplet spectrum and in attempting to narrow it to the most appropriate size for biological effectiveness while minimizing the production of smaller, drift-prone droplets. References related to this research are: Boize and Dombrowski, (1976); Goering and Smith, (1978); Lawson and Uk, (1979).

The spinning disc or cone type atomizers being introduced for CDA spraying are potentially usable on both ground-rig and aircraft, while the nozzles and formulations involved in the ULV approach are primarily suited to aerial application. Inherent in ULV spraying is the replacement of aqueous solutions by oil-based carriers, to eliminate droplet spectrum change through evaporation of the solvent component.

Considerable research has been undertaken on aircraft spray operations, including efforts to reduce drift. Much of this effort has gone into boom nozzle spacing and arrangement, in an effort to avoid unwanted effects imposed by the aircraft vortex, specifically non-uniform patterns and/or excessive spray drift (c.f. a number of papers by Akesson and Yates over the past two decades). For aircraft, as for helicopters, it is potentially possible to produce nozzle type, pressure and formulation combinations designed to reduce the production of small droplets, without necessarily affecting the swath deposit pattern thereby. The reason is that the latter is much more controlled by wing tip vortex effects (or rotor vortex for helicopters) than by the initial droplet emission pattern at the nozzle. Modelling of vortices has been attempted (Morris, 1978) and leads to the establishment of "effective" release heights in place of nominal ones as set by the boom and nozzle location above ground. Helicopter

research has been much less extensive, and tends to be limited to specific application situations (e.g. Yates, Ogawa and Akesson, 1974).

Both groundrig and aircraft spraying systems have been tested in field trial operations, designed to yield a measure of initial drift as a function of emission parameters and atmospheric conditions. Several groups have been active in this work, notably at the University of California in Davis (c.f. papers by Akesson and Yates), at the Universities of Missouri and Illinois (Goering, Butler et al) and at Cranfield, England (Sayer, Bache, Lawson and Uk) as well as in Saskatchewan at Agriculture Canada and at Saskatchewan Research Council (Grover, Maybank, Shewchuk and Yoshida). Techniques commonly involve the spraying of a single swath, with sampling devices being set out to measure some at least of the following parameters: swath deposit density; off-swath deposit density at various downwind distances; airborne concentrations at downwind distances; droplet size spectra for each of the components.

Results clearly identify the drift-prone fraction as being that portion of the droplet spectrum below about 100μ initial diameter. The fraction of these sizes that does drift off-swath increases with ambient windspeed and effective release height. Drift is also positively correlated with groundrig speed and, for aircraft, with vortex strength. On the other hand atmospheric turbulence plays only a minor role close to the sprayed swath, its influence becoming measurable only beyond the first few tens of metres. Commonly, in these field trial studies, sampling of the drift cloud or of the off-target deposit extended only some few hundred metres downwind.

With the muliplicity of variables, it becomes particularly difficult

to determine the relative importance of each. Goering and Butler (1973) attempted a multivariate analysis approach on their twin-boom trials, but because airborne concentrations weren't measured this led to ambiguous responses of the drift cloud to changes in windspeed and to downwind turbulence. A similar trial format, by Grover, Kerr, Maybank and Yoshida (1978), but incorporating both airborne mass and deposit mass measurements downwind, clearly identified that initial airborne drift increased linearly with windspeed (over a limited speed range at least), and with increasing vehicle turbulence, but that the close-in ground deposit amounts decreased.

Beyond the action of the sprayer-impressed variables, spray drift may be treated as a pollutant dispersal problem and a number of models have been developed. Most of these relate to particle diffusion from various industrial sources and are based on a milestone paper by Csanady (1963). Adaptation to pesticide application requires that a suitable droplet spectrum (initial and final) be identified or assumed, together with dimensions for a line source based on the vehicle velocity, turbulence (vortex) and release height. With these initial conditions set, realistic values of windspeed, air temperature, humidity and stability can be fed into the relevant equations, resulting in values of either ground deposit amounts or airborne concentrations at various downwind distances. Recent papers describing these processes are: Bache and Sayer (1975), Reid (1979), Reid and Crabbe (1980), and Thompson and Ley (1983).

Two distinct models have been developed by these authors, one based on gradient transfer, the other on summing large numbers on individual droplet trajectories (Markov chain approach). Both require considerable computation time and rely on similar input parameters. According to Reid

and Crabbe's analysis, the agreement with observations was good out to 30 km (when simulating a forest insecticide scenario) for the gradient transfer model; indeed the overall difference between the predictions from the two models was relatively small.

While the first three papers listed above considered the drift situation appropriate to aircraft operation, the fourth (Thompson and Ley, 1983) specifically addressed spray drift from groundrigs. Recently, Crabbe (1983) modified his and Reid's model to provide drift estimates for aerially-applied 2,4-D herbicide sprays in an agricultural setting. Again, instead of dealing with ground deposits, the targets were considered to be vertical blocks of human dimensions so that airborne concentrations at various distances were determined.

This brings up the area where major analysis problems still remain: the interaction of drifting droplets with foliage and other obstacles just as the ambient turbulence regime is being drastically altered at canopy height. There are a few papers where this has been investigated in the field (e.g. Landsberg and Thom, 1971; Byass and Lake, 1977; Raupach and Thom, 1981) or in wind tunnel studies, but so far the effects observed have not been successfully incorporated into the spray drift models (Thompson and Ley, 1983).

## 4. PARAMETERS TO MEASURE FOR SPRAY DRIFT EVALUATION

From the literature review and the identification of factors affecting spray drift, it is apparent that a detailed investigation would include both model calculations and field trials for confirmation of model predications. Hence two sets of measurements should be considered,

or rather, the parameter measurement be taken in such a way as to satisfy these two approaches to drift delineation.

(i) Rate of emission - This clearly should be provided by fluid monitoring gauges in the feed lines, for all types of spray boom and nozzle combinations. Together with the vehicle speed (ground speed in the case of aircraft and helicopters). This measurement gives the litres of emitted solution per metre of swath traverse. Together with the solution concentration figure for the actual pesticide being used, the active ingredient being disseminated per metre can be determined.

(ii) Release height - While this, in principle, could be calculated from the boom and nozzle location and orientation and give a usable figure for field trial measurement, it has to be known more accurately for useful drift modelling calculations. This is especially true for aircraft and helicopters, where vortices will alter the nominal drift height. While wind tunnel tests and wake modelling such as undertaken by Morris (1978) may provide usable values, the reflection effect, when a spray aircraft is flown very close to the ground and the lower vortex edge "bounces", is a significant complicating factor. Direct field measurements, involving photogrammetry, would be advisable for best determination of this model input parameter.

(iii) Initial droplet spectrum - This is clearly the most important parameter of all for the spray drift calculation process. It can be, and usually is, measured in static laboratory tests, for various combinations of nozzle type, solution mix, and hydraulic pressure. When this is provided in sufficient detail and for the appropriate nozzle and solution, it usually suffices for groundrig applications. However, for

aircraft and helicopters, there is strong evidence (see for example Saunders, Tate and Ware, 1976) that the vehicle's forward speed, plus the boom and nozzle orientation, play a major role in the break-up process, completely altering the drop size spectrum found in laboratory tests. Lawson and Uk (1979) in fact recommend that wherever possible, droplet spectra be measured in the field.

This is not easy to do by most techniques presently available. Common methods involve collection of a sample of the droplets on some solid surface, either by impaction or aspiration. The resulting stains are subsequently scanned and sized microscopically. There are two basic problems in all such approaches: how representative is the sample, and how early was it caught? Impaction efficiency varies with droplet size, so that the smaller sizes may frequently be under-represented. The time of collection problem relates to the rapidity with which the water component will begin to be lost through evaporation. This again affects the smaller size categories more than the larger. One way to avoid both problems is to collect the complete output for a small emission time in a closed container, in which the air is close to 100% RH. Clearly such a technique is not readily adaptable to field operation, or even to dynamic emission tests in a wind tunnel.

A potential breakthrough in the rapid measurement of small droplets in air involves the use of a laser scanner. It has been used successfully both in static and in wind tunnel investigations of spray nozzle output (Akesson and Yates, 1981). It is equally capable of measuring the droplet spectrum for flat fan and CDA spinning-cone type nozzles though more careful placement of the laser beam is necessary for the

former to ensure scanning a representative droplet sample.

No matter where or how the droplets coming from a spray device are sized, it is essential that the nature of the entire spectrum be designated. While useful for some purposes, the VMD or the number median diameter (NMD), is simply insufficient to characterize the complete spectrum. At the very least some measure of the range (such as standard deviation) must be given, or the fraction of volume present in drift-prone droplet sizes (frequently identified as those below 100μ diameter). Better, and generally necessary for model prediction is provision of volume amounts in six or more size range classes, covering most of the total output.

(iv) Meteorological parameters - For actual drift measurement one is essential, the wind speed at some height. A commonly-used height for both groundrig and aircraft trials (and one that relates to agro-meteorological studies in general) is 2 metres. This is also the height at which wind direction is commonly measured. While the latter parameter is necessary for actual drift measurement trials, directional variations in time are not usually entered into the various drift models, as an indefinitely long line source is used.

Two other meteorological parameters must be measured if aqueous solutions are used, viz air temperature and humidity. Their values at the time of the spraying are necessary to permit the final droplet size distribution, after evaporation of the water component, to be calculated from the initial one.

For both measurement and prediction purposes, it is also necessary to categorize the degree of instability of the air at the time of spraying.

A number of specific measures or calculated parameters exist, such as the stability index, Richardson number, eddy diffusion coefficient, etc. All are derived from some combination of temperature and windspeed variation with height. Hence it is not enough to measure these two variables at only 2 metres; at least one and preferably two or more other heights are necessary. Present practice suggests standardizing on at least 3 of the following four: 1/2, 2, 4 and 10 metres above ground, as a requirement for prediction and observation comparison.

The foregoing parameter measurements should provide for the capability of modelling a spray drift scenario in any circumstances. From the initial droplet spectrum to the final one requires the application of evaporation calculations needing inputs of solution strength, temperature and humidity, which together with terminal velocity values (also calculable given certain assumptions at the nozzle) permit the initial off-target drift cloud to be categorized.

For comparison of the model to actual drift magnitudes at various downwind distances, several spray amount measurements have to be taken.

(i) Deposit mass density in the target area. In principle, the difference between this pesticide amount per metre of traverse and the emission rate would be a measure of off-target drift, but the imprecision of the measurements does not usually allow for a good estimate of the relatively small off-target loss. From the deposit density data, however, the initial effectiveness of the spray mechanism can be gauged, via measurements of deposit density uniformity (in terms of standard deviation or coefficient of variation along the swath).

(ii) Size distribution of the swath deposit, which should be close

to the initial emission one except at the small droplet end.

(iii) Initial off-target airborne droplet concentration. This should be measured at several heights, sufficient to bracket the cloud in the vertical (easily achieved for groundrig application, less so for aircraft or helicopter operations). While spray drift modelling can deal with the total droplet cloud as emitted at the nozzle, the measurement of airborne mass at the immediate edge of the swath permits a second predictive computation to be made.

(iv) Size distribution of initially drifting droplets. This parameter, taken after a short, measurable travel downwind under measured air temperature and humidity, will provide information on how well the basic calculations handle evaporation to final droplet size.

(v) Downwind deposit densities and airborne concentrations at several heights. These data will provide for model prediction checks at one or more downwind distances, say 30, 100 and 400 metres. If both ground deposits and concentrations are measured at these distances, one can obtain a double comparison to the model, yielding values for what fraction has fallen out, and for what is still airborne but reduced by both fallout and diffusion in the vertical. Clearly, these measurements will be limited by analytical sensitivities, but should these permit, deposits or airborne concentrations (or both) could be assessed at greater downwind distances, perhaps of several km on occasion.

## 5. DATA REQUIREMENTS FOR DEVELOPING SPRAY VEHICLE PROTOCOLS

Tabulated data exist or may be calculated for evaporation times of droplets of various sizes. This information, together with final

diameters (dependent on non-volatile fraction, commonly 1-10% of total) should be collated into a readily usable form for air temperatures in the range of 10-30C and for relative humidities of 30, 50 and 70% say.

Secondly, terminal velocities for evaporating droplets can be calculated, in conjunction with the above data. Ventilation effects may be incorporated as well. With this data base, the data requirements for the equipment can be ascertained.

For all vehicles, it will be essential to determine the initial droplet size spectrum that a nozzle produces at various hydraulic pressures. This should also be determined for pesticide type and solution strength, but as most nozzles are specifically recommended for a given application rate, the pressure and fluid being used may have only 2 or 3 relevant settings. Consistency of spectrum measuring techniques is essential here, and once a series of spectra has been obtained for several nozzles of a certain type, it may be possible to determine from correlation parameters how a different size nozzle tip would behave.

For nozzles intended solely for use on groundrigs, the droplet spectrum may be determined in static testing. However, for aircraft and helicopter operations, the initial droplet spectrum must be measured under windspeed conditions (and at nozzle orientations to it) that are typical of the field operation. For the relatively few nozzle sizes that are proposed for use both on groundrigs and aircraft, clearly the initial size spectrum should be determined both ways.

As mentioned previously it will not be sufficient to characterize the spectrum simply by a single average droplet size (VMD, NMD or other). Full characterization should be tabulated as percentages in several size

classes, at least for the smaller drift-prone portion of the distribution.

For groundrig vehicles, nozzle orientation and height above ground, plus droplet velocity and trajectory at the point of emission may be combined to provide an effective release height for the spray. This height may vary a bit with hydraulic pressure in the boom, as the droplet emission pattern is altered thereby, but the differences over the range of recommended settings is probably small. At the higher ground speeds that some spray vehicles are capable of, 20-40 km/h, say, it may be necessary to consider the effect of vehicle-induced turbulence, as well, in characterizing the effective spray droplet release height.

For aircraft and helicopters, this last term dominates release height, and actual nozzle parameters assume only minor importance. For fixed-wing aircraft, the magnitude of wingtip vortices is a complicated function of weight, airspeed and wing loading. It may be estimated or else measured in wind tunnel tests. Typical values for each spray plane being used should be known, as well as the change in them between full-load and no-load conditions. A similar requirement would apply to helicopters, except here it is the rotor vortex that is of concern.

Due to ground-interaction (vortex "bounce" or reflection) actual flying heights would be a data requirement as well, both for fixed-wing aircraft and for helicopters. For standardization, this should be the wheel height, or perhaps the spray boom height, that is specified.

A final requirement, to provide a reliable figure for effective release height, would be to specify both the boom location with respect to the wings or rotor, and the nozzle spacing along it. This last is frequently varied simply on a "trial and error" basis to provide for

better swath uniformity, but in fact the nozzle location is being adjusted so as to emit the spray most effectively within and around the wing tip or rotor vortices. Recommended boom configurations can be arrived at once the actual vortex pattern and magnitude is known.

## 6. CONCLUSIONS

With the above data being available it should be possible to specify appropriate equipment settings to minimize drift, under any particular set of atmospheric conditions. The vital question is: can a single "off-set" distance be specified for all agricultural pesticide applications that will keep off-target spray drift below an acceptable limit? The answer is "probably not" given the plethora of chemicals, spray equipment and operating conditions presently in use or permitted. However, it should be possible to narrow these variations down considerably to a relatively few approved ones, for which a safe off-set distance (or small range of distances) can be assigned.

The starting point is clearly to define what might be acceptable as a deposit in an off-target area for a range of approved herbicides and insecticides. This would be some value, 1/n, of the amount being applied to the target. The factor, n, might be set at 100 or 1000 (i.e. reduction to 1% or .1% respectively). Reliable modelling prediction would be used to set the distance required for the initial drift to decrease to this percentage under various atmospheric conditions, both for a single swath and, more importantly, for a total field operation. This information could then be combined with the identification of those spray systems capable of maximizing the ratio of target deposit

rate to initial drift (by droplet size control, primarily) so as to ensure that airborne amounts and deposits beyond a certain distance downwind were below the 1/n value. That such equipment exists, but isn't always used under appropriate wind and turbulence regimes, is suggested by Crabbe and Curry's calculations (1983). They found that the drift varied in their two scenarios such that the amount still airborne 200 m downwind of a single sprayed swath is either 0.06% or 43% of the amount emitted, the difference being almost entirely due to the initial droplet size spectrum being produced at the aircraft spray boom.

It is obviously unwise to declare for a definite value at this stage of the assessment process. Nevertheless, one might infer from the above data that a realistic off-set distance might lie between 100 and 1000 metres for nearly all combinations of equipment and weather that should be (not are being) used for agricultural pesticide application. A much narrower range, perhaps 200-400 m, could be recommended following only modest further analysis.

## 7. REFERENCES AND SELECTED BIBLIOGRAPHY

This list contains, in addition to papers specifically cited in the text, a number of additional entries to provide for a broader access to the scientific literature on the topic of spray drift research. They have been selected, somewhat subjectively, using the following criteria:

(i) Relevance to droplet production and spray drift, as opposed to chemicals, efficacy, environmental hazards, vapour loss, etc.

(ii) Topicality, generally limiting the entries given here to the more recent papers coming from active research groups.

(iii) The presence in the paper of a broad overview and/or the inclusion of a sizeable list of references (this criterion, together with the preceding one, would allow a reader to "back-track" through the literature.

(iv) Relative availability, in English, of the paper, which weights the selection towards papers in scientific journals, and away from the more comprehensive coverage that might be available in Institute reports, etc., by the same authors.

The bibliography has been divided into four broad categories: (i) books and bibliographies; (ii) papers on nozzles, emission characteristics and sprayer systems; (iii) papers dealing with field experiments and observations; (iv) papers describing drift and deposition modelling. Copies of a few of these papers have been included in the Appendix 2 of this report. They are marked with an asterisk in the left hand margin of the list.

(i) Books and Bibliographies

Anderson, W.P. 1977. Weed Science: principles. Publ. by West Pub. Co. 598 pp.

Csanady, G.T. 1973. Turbulent diffusion in the environment. Publ. by Reidel, Dordrecht. 248 pp.

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(iii) Field experiments and observations

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* Lawson, T.J., and S. Uk. 1978. The influence of wind turbulence, crop characteristics and flying height on the dispersal of aerial sprays. Atmos. Environ. 13: 711-715.

Maybank, J., K. Yoshida and R. Grover. 1974. Droplet size spectra, drift potential and ground deposition pattern of herbicide sprays. Can. J. Plant Sci. 54: 541-546.

* Maybank, J., K. Yoshida, and R. Grover. 1978. Spray drift from agricultural pesticide applications. J. Air Pollut. Control Assoc. 28: 1009-1014.

Maybank, J., K. Yoshida, S. Shewchuk and R. Grover. 1976. Comparison of swath deposit and drift characteristics of groundrig and aircraft herbicide spray systems; report of the 1975 field trials. Sask. Res. Council Rep. P-76-1, 25 p.

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(iv) Drift and deposition modelling

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APPENDIX I. A selection of tables and graphs from recent reports.

Included here are a few illustrations of nozzle parameters or research findings relevant to pesticide spray production and drift. The entire report or paper has not been included in Appendix II due usually to its bulk. The source is given on each figure, with full citation unless previously cited in the bibliography.

| | |
|---|---|
| Appendix I - 1 | Table of nozzle emission rates. |
| Appendix I - 2 | Droplet size spectra and wind speed frequencies. |
| Appendix I - 3 | Illustration of how the droplet size distribution may vary between static (laboratory) and dynamic (aircraft) testing for the same nozzle. |
| Appendix I - 4 | Factors affecting initial off-target spray drift. |
| Appendix I - 5 | Illustration of relationship between airborne spray drift and off-target deposition, for aerial application. |
| Appendix I - 6 | Modelling of aircraft wakes. |
| Appendix I - 7 | Off-target spray deposit predictions. |
| Appendix I - 8 | Off-target spray drift predictions. |

**TABLE 1. APPLICATION VOLUMES — FLAT SPRAY NOZZLES**

| NOZZLE | | | | litres per hectare 50 cm spacing | | | | |
|---|---|---|---|---|---|---|---|---|
| Delavan 65 or 80° | Teejet | Pressure kPa | Output L/min | 6 km/h | 8 km/h | 10 km/h | 12 km/h | 18 km/h |
| LFI | 65 & 8001 | 200 | 0.32 | 64 | 48 | 39 | 32 | 21 |
| | | 250 | 0.36 | 72 | 54 | 43 | 36 | 24 |
| | | 275 | 0.38 | 76 | 57 | 45 | 38 | 25 |
| LF.5 | 65 & 80015 | 200 | 0.48 | 97 | 72 | 58 | 48 | 32 |
| | | 250 | 0.54 | 108 | 81 | 65 | 54 | 36 |
| | | 275 | 0.57 | 113 | 85 | 68 | 57 | 38 |
| LF2 | 65 & 8002 | 200 | 0.65 | 129 | 97 | 77 | 64 | 43 |
| | | 250 | 0.72 | 144 | 108 | 86 | 72 | 48 |
| | | 275 | 0.76 | 151 | 113 | 91 | 76 | 51 |
| LF3 | 65 & 8003 | 200 | 0.97 | 193 | 145 | 116 | 97 | 64 |
| | | 250 | 1.08 | 220 | 162 | 130 | 108 | 72 |
| | | 275 | 1.13 | 230 | 170 | 136 | 113 | 76 |
| LF4 | 65 & 8004 | 200 | 1.29 | 260 | 193 | 155 | 129 | 86 |
| | | 250 | 1.44 | 290 | 220 | 173 | 144 | 96 |
| | | 275 | 1.51 | 305 | 230 | 181 | 151 | 101 |
| LF5 | 65 & 8005 | 200 | 1.61 | 320 | 240 | 193 | 161 | 107 |
| | | 250 | 1.80 | 360 | 270 | 220 | 180 | 120 |
| | | 275 | 1.88 | 375 | 285 | 230 | 188 | 126 |
| LF6 | 65 & 8006 | 200 | 1.93 | 390 | 290 | 230 | 193 | 129 |
| | | 250 | 2.16 | 430 | 320 | 260 | 220 | 144 |
| | | 275 | 2.26 | 450 | 340 | 270 | 230 | 151 |

**NOTE:** Tables of application volumes are also available for other nozzle sizes, spacings and forward speeds.

Example of application rate tables available to farmers.

(from "Field Sprayers" Man. Dep't. of Agriculture. publ: AgDex 744-1; June, 1982)

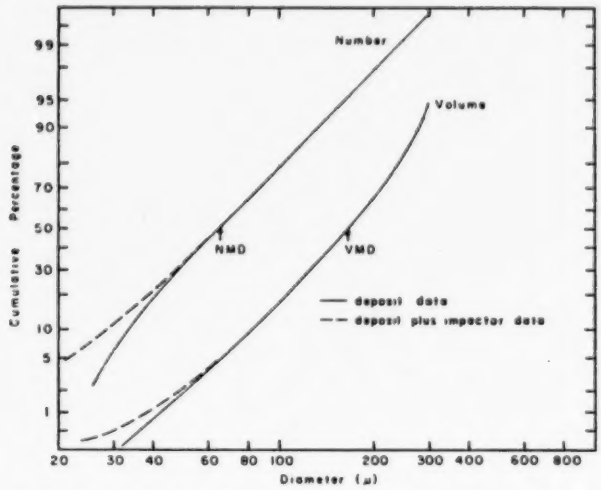


**Fig. 1 Typical droplet-size distribution produced by a herbicide spray nozzle at 40 psi pressure**

Example of deposit size distribution showing the effect of off-swath droplet drift on the spectrum.

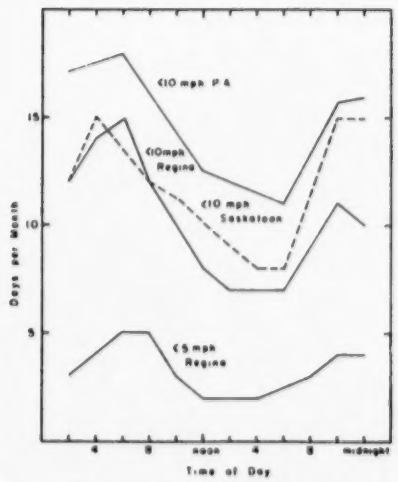


**Fig. 4 Frequency of light hourly winds during June at Regina, Sask., and at Prince Albert**

Variation of usable windspeeds with time of day (from Maybank, J. and K. Yoshida. 1969. Delineation of herbicide drift hazards on the Canadian prairies. Trans. ASAE 12: 759-762

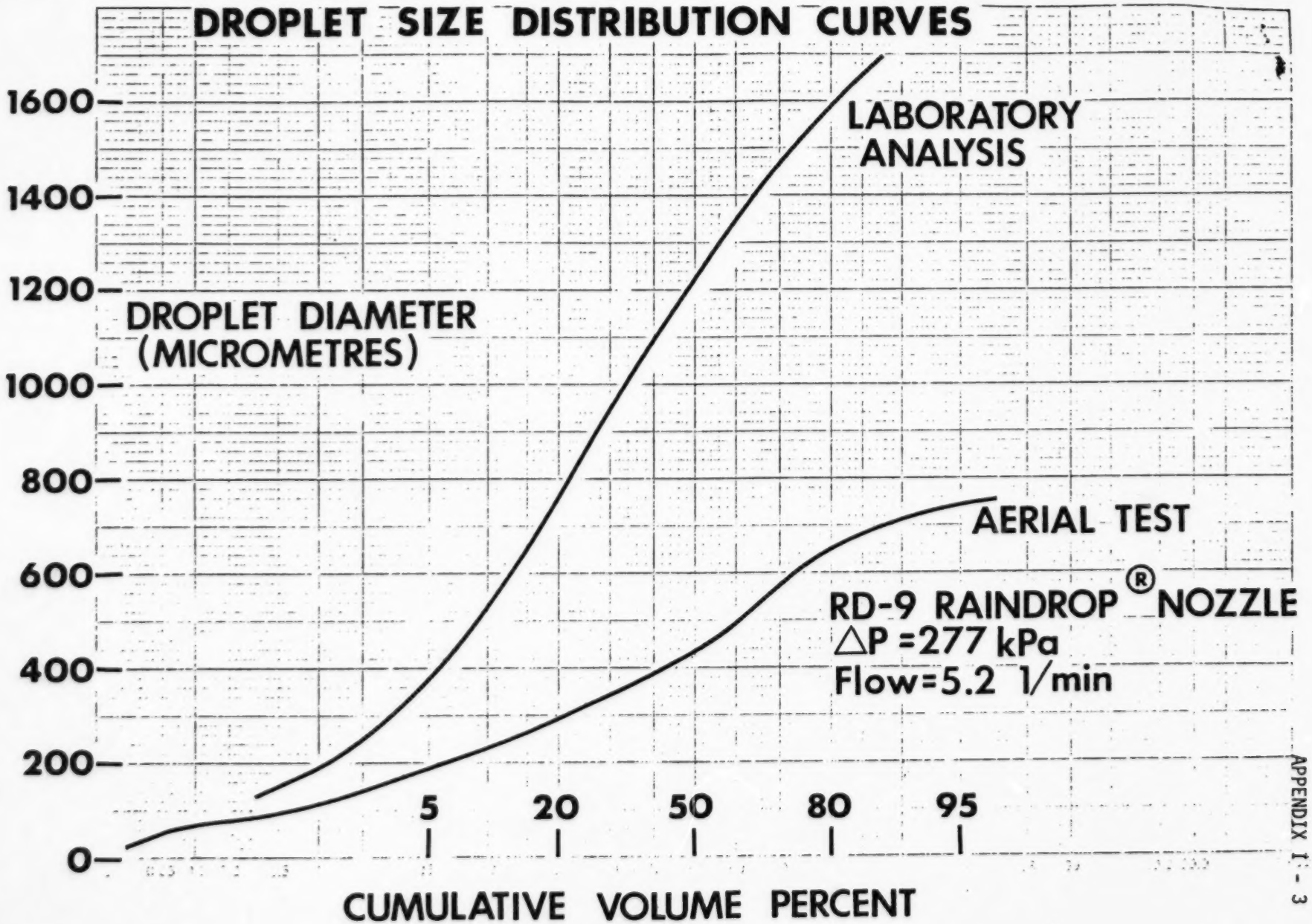


Figure 6. Comparison of laboratory and field data for Raindrop nozzle.
(from Saunders, Tate and Ware; 1976)

The following conclusions were drawn from the results of the drift study:

1. The fluorescent tracer dyes used were degraded substantially in sunlight and thus the results had to be corrected for dye degradation.
2. Drift deposits in relation to downwind distance could be fitted with a curve having only slight curvature on log-log paper.
3. The E-102 spray thickener reduced both the amount of drift deposits and the amount of spray loss by increasing deposits within the swath.
4. Lowering the nozzle height decreased the drift deposits.
5. Lowering the nozzle pressure decreased the spray loss.
6. Low temperatures and high relative humidity were associated with decreased drift and decreased spray loss.
7. Since the Richardson number was highly correlated with the Yates stability ratio, either could serve as an indicator of air turbulence.
8. Increased air turbulence produced greater spray loss but less downwind drift deposits.
9. Increased horizontal wind speed produced greater spray loss but produced either greater or smaller drift deposits, depending upon other meterological factors.

Conclusions reached from regression analysis of a series of paired-boom sprayer studies (from Goering and Butler; 1973)

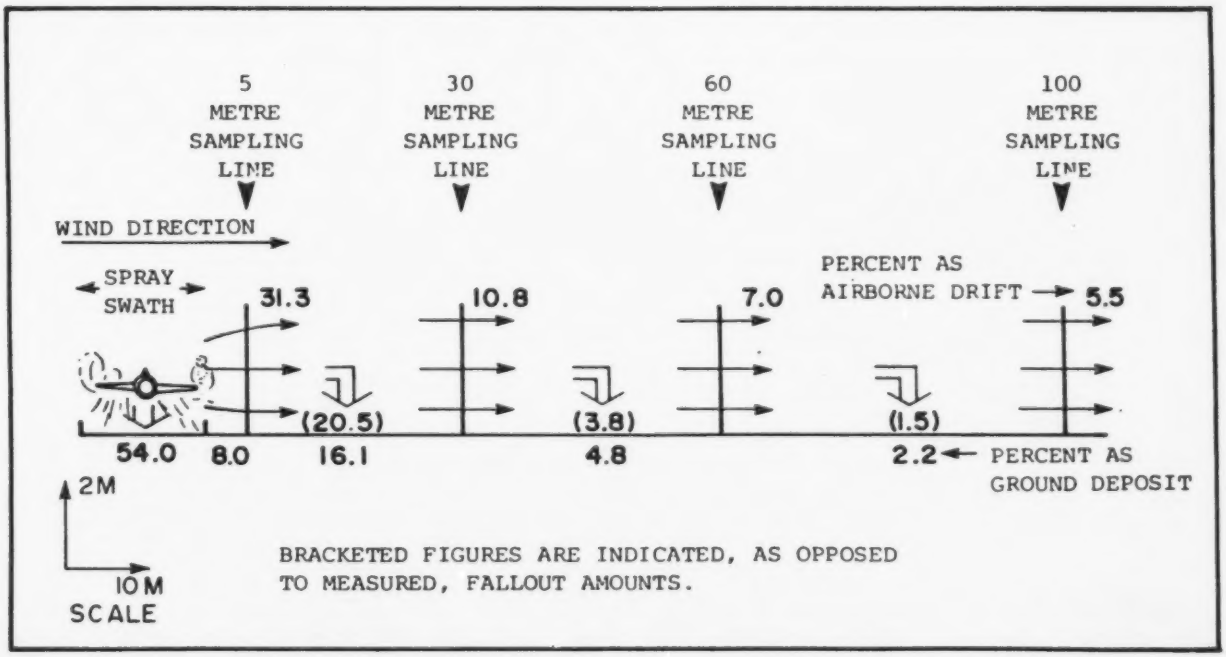


**Figure 7. Schematic diagram of aerial spray mass budget.**

(from J. Maybank. 1981. An assessment of the efficiency and effectiveness of herbicide applications. Proc. of Sixth Australian Weeds Conf. Vol. 2: 167-178)

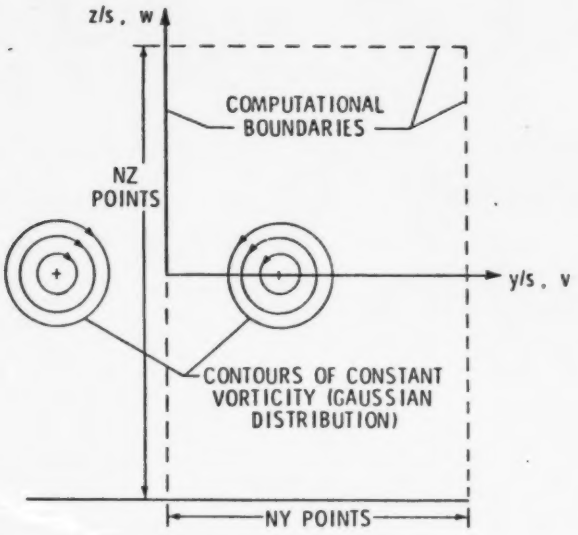


Figure 1.- Initial conditions for vortex dissipation simulation.

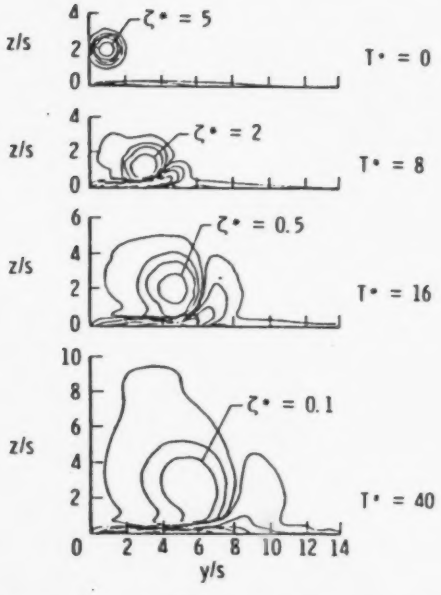


Figure 2.- Influence of ground on vortex dissipation and movement.

An example of the modelling of aircraft wakes (from Morris, 1978).

TABLE 4

**Effects of atmospheric stability on deposit densities**

| *Drop size, μm* | *Wind speed, m/s* | *Distance downwind, m* | *Deposit densities, drops/m²* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *Non-evaporating drops* | | | | *Evaporating drops* | | | |
| *Release height, m* | | | *0·2* | | *1·0* | | *0·2* | | *1·0* | |
| | | | *N** | *U†* | *N* | *U* | *N* | *U* | *N* | *U* |
| 50 | 2 | 10 | 130 | 170 | 400 | 300 | 55 | 55 | 55 | 50 |
| | | 50 | 5 | 12 | 34 | 33 | 12 | 10 | 18 | 14 |
| | | 100 | 1·0 | 3·4 | 8 | 11 | 5 | 4·3 | 10 | 7 |
| | | 500 | 0·03 | 0·24 | 0·28 | 0·9 | 0·7 | 0·9 | 1·3 | 1·6 |
| | 5 | 10 | 190 | 180 | 230 | 200 | 50 | 56 | 50 | 60 |
| | | 50 | 24 | 21 | 50 | 40 | 10 | 10 | 17 | 14 |
| | | 100 | 7 | 7 | 17 | 14 | 5 | 5 | 8 | 7 |
| | | 500 | 0·43 | 0·6 | 1·1 | 1·4 | 0·9 | 1·0 | 1·6 | 1·3 |
| 100 | 2 | 10 | 0·2 | 10 | 80 | 200 | 1 0 | 12 | 140 | 190 |
| | | 50 | 0 | 0·1 | 0·08 | 26 | 0 | 0 24 | 4·2 | 6 |
| | | 100 | 0 | 0 | 0 | 0·5 | 0 | 0 12 | 1·8 | 2·8 |
| | | 500 | 0 | 0 | 0 | 0·1 | 0 | 0·01 | 0·22 | 0·48 |
| | 5 | 10 | 80 | 100 | 500 | 420 | 80 | 120 | 400 | 370 |
| | | 50 | 1·3 | 2·9 | 12 | 22 | 1·4 | 2·1 | 9 | 9 |
| | | 100 | 0·23 | 0·6 | 2·0 | 3·8 | 0 5 | 0·7 | 3·7 | 3·8 |
| | | 500 | 0·01 | 0·02 | 0 03 | 0·20 | 0 06 | 0 07 | 0·45 | 0·6 |
| 150 | 5 | 10 | 3·6 | 15 | 280 | 320 | 5 | 16 | 300 | 300 |
| | | 50 | 0 | 0 | 0·4 | 2·8 | 0 | 0 04 | 7 | 3 |
| | | 100 | 0 | 0 | 0 | 0 3 | 0 | 0 01 | 0 04 | 0 25 |
| | | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 01 |

**N* = neutral stability
†*U* = unstable conditions (Monin-Oboukov stability length = −5 m (for wind speed of 2 m/s) and −20 m for 5 m/s wind, corresponding to moderate-to-strong sunshine)

TABLE 3

**The influence of drop size on drift**

| *Wind speed, m/s* | *Distance downwind, m* | *Deposit densities, drops/m²* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *50 μm drops* | | *100 μm* | | *150 μm* | | | *200 μm* | |
| *Effective release height, m* | | *0·2* | *1·0* | *0·2* | *1·0* | *0·2* | *0·5* | *1·0* | *0·2* | *1·0* |
| 2 | 10 | 55 | 50 | 12 | 190 | 0 | 0·5 | 12 | 0 | 0 |
| | 50 | 10 | 14 | 0·24 | 6 | 0 | 0 | 0 01 | 0 | 0 |
| | 100 | 4·3 | 7 | 0 12 | 2 8 | 0 | 0 | 0 | 0 | 0 |
| | 500 | 0·9 | 1·6 | 0 01 | 0·48 | 0 | 0 | 0 | 0 | 0 |
| 5 | 10 | 56 | 60 | 120 | 370 | 16 | 80 | 300 | 0 | 120 |
| | 50 | 10 | 14 | 2·1 | 9 | 0·04 | 1·0 | 3 0 | 0 | 0·08 |
| | 100 | 5 | 7 | 0·7 | 3·8 | ~0 01 | 0 10 | 0·25 | 0 | ~0 01 |
| | 500 | 1·0 | 1·3 | 0 08 | 0·6 | 0 | 0 | 0 02 | 0 | 0 |
| 10 | 10 | 130 | 130 | 170 | 330 | 90 | 270 | 430 | 29 | 430 |
| | 50 | 10 | 18 | 8 | 27 | 1·0 | 5 | 15 | 0·10 | 4·4 |
| | 100 | 6 | 9 | 1·5 | 4 | 0·15 | 0·8 | 2·0 | ~0 01 | 0·6 |
| | 500 | 0·9 | 1·5 | 0·12 | 0·5 | <0 01 | 0 02 | 0 04 | 0 | <0·01 |

**Influence of various factors in the model predications for off-target spray deposition (from Thompson and Ley; 1983)**

Table I-1. Numbers and velocities of the droplets in the drift cloud resulting from the D6-46 and Teejet nozzles.

| Initial Droplet Diameter (mid) (μm) | Terminal Velocity $V_{SI}$[α] ($cm.s^{-1}$) | Evaporated Diameter (μm) | Terminal Velocity $V_{SE}$[β] ($cm.s^{-1}$) | Number of Droplets D6-46 Nozzle | Teejet Nozzle |
|---|---|---|---|---|---|
| 12.5 (0-25) | 0.49 | 5.6 | 0.10 | $1 \times 10^5$ | $3.45 \times 10^9$ |
| 37.5 (25-50) | 4.35 | 16.9 | 0.90 | $1.10 \times 10^5$ | $6.47 \times 10^8$ |
| 66.7 (50-83.3) | 13.60 | 30.0 | 2.84 | $4.96 \times 10^4$ | $1.49 \times 10^7$ |
| 100.0 (83.3-116.7) | 26.80 | 45.0 | 6.38 | $3.99 \times 10^4$ | $7.36 \times 10^6$ |
| 133.3 (116.7-150) | 42.10 | 60.0 | 10.77 | $4.34 \times 10^4$ | $3.27 \times 10^6$ |
| 166.7 (150-183.3) | 58.10 | 75.0 | 16.40 | $1.18 \times 10^5$ | $1.29 \times 10^6$ |
| 200.0 (183.3-215.7) | 72.60 | 90.0 | 22.48 | $2.10 \times 10^5$ | $8.17 \times 10^5$ |

[α] $V_{SI}$ = Terminal velocity of the initial droplets.

[β] $V_{SE}$ = Terminal velocity of the evaporated droplets.

Table 4-1. Exposure to bystanders from an aerial spray of 2,4-D, as predicted by the model using the Prairie scenario.

| Distance from spray line (m) | Wind speed at 2 m agl[α] ($m.s^{-1}$) | Exposure: Dermal (μg) | Exposure: Oral[β] ($\mu g.min.L^{-1}$) | Exposure: Inhalation[β] ($\mu g.min.L^{-1}$) |
|---|---|---|---|---|
| 50 | 1.5 | 1.36 | $2.68 \times 10^{-3}$ | $1.35 \times 10^{-5}$ |
| | 3.0 | 100.60 | $1.93 \times 10^{-3}$ | $9.57 \times 10^{-6}$ |
| 100 | 1.5 | 0.32 | $1.37 \times 10^{-3}$ | $8.53 \times 10^{-6}$ |
| | 3.0 | 19.08 | $1.08 \times 10^{-3}$ | $5.03 \times 10^{-6}$ |
| 200 | 1.5 | 0.058 | $4.37 \times 10^{-4}$ | $4.32 \times 10^{-6}$ |
| | 3.0 | 3.06 | $4.70 \times 10^{-4}$ | $2.77 \times 10^{-6}$ |
| 400 | 1.5 | 0.010 | $1.52 \times 10^{-4}$ | $1.87 \times 10^{-6}$ |
| | 3.0 | 0.55 | $1.38 \times 10^{-4}$ | $1.20 \times 10^{-6}$ |
| 800 | 1.5 | 0.002 | $5.06 \times 10^{-5}$ | $8.57 \times 10^{-7}$ |
| | 3.0 | 0.18 | $4.78 \times 10^{-5}$ | $3.57 \times 10^{-7}$ |

[α] agl = above ground level.

[β] The units are time-integrated atmospheric concentrations of herbicide; the mass of pesticide ingested is determined by multiplying by the breathing rate.

**Model predictions of the airborne droplet concentrations at various downwind distances from an aerial spray application (from Crabbe and Curry; 1983)**

APPENDIX II A few recent and relevant reprints.

Appended here are copies of a few of the papers cited in the bibliography. Selection has been based on:

(i) relevance and topicality

(ii) reference and review coverage, to enable a literature search to be mounted

(iii) lack of bulk, to keep the Appendix of manageable size

(iv) availability before March 31, 1984 (the completion date for the contract). Unfortunately, perhaps, the most important criterion, but inevitable given the time delay in receiving reprints or computer retrieval copy. It is hoped to issue a second volume to this report, consisting of an extension of this Appendix.

Appendix II - 1 Lawson and Uk (1979)

Appendix II - 2 Maybank, Yoshida and Grover (1978)

Appendix II - 3 Yates, Akesson and Cowden (1974)

Appendix II - 4 Reid and Crabbe (1980)

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# THE INFLUENCE OF WIND TURBULENCE, CROP CHARACTERISTICS AND FLYING HEIGHT ON THE DISPERSAL OF AERIAL SPRAYS*

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(*First received* 16 *August* 1978 *and in final form* 12 *December* 1978)

**Abstract**– A series of aerial spray field trials using drops of size 10–230 $\mu$m were conducted to determine how the total amount of airborne spray varied with spray release height, drop size, downwind distance, turbulent airflow conditions and the nature of the underlying surface (wheat or fallow). By comparing the results with the predictions of a theoretical model of spray dispersal under turbulent conditions, it was possible to quantify both the removal efficiency of the underlying surface for various drop sizes, and the influence of the aircraft wing-tip vortices in changing the effective spray release height. The results are presented so that the total amount of airborne drift can be predicted from any atomiser, once the drop size spectrum produced by the atomiser is known. The variability due to turbulence of the quantity of airborne spray between individual spray runs is assessed and implications drawn regarding the number of repeat trials necessary to show significant results.

## 1. INTRODUCTION

The rational application of chemicals to control plant pests and diseases aims to optimise the size of drops leaving the atomiser so as to maximise the efficiency of spray delivery to the target organisms. There is increasing evidence that better spray collection and retention by the majority of biological targets in their natural environment is obtained when the drop diameter is smaller than 100 $\mu$m (e.g. Himel, 1969; Uk, 1977; Lake, 1977). Although the question of spray drift out of a field has always been a problem with the larger drops used in low volume and high volume applications, the use of sub-100 $\mu$m drops in ultra-low-volume applications reinforces the need for further understanding of drift and its relation to such factors as wind speed, spray release height and crop characteristics.

The assessment of spray drift from aerial applications to date has involved mainly ground level measurements of spray deposits at various distances downwind from the sprayed field (e.g. Akesson and Yates, 1974; Yates *et al.*, 1974; Yeo and Thompson, 1954). Measurements have either been made on artificial collecting surfaces to yield drop size and number, or on natural surfaces where only chemical quantity is obtained. Results of spray dispersal measurements restricted to near ground level are incomplete and difficult to relate to the removal efficiency by the crop of different drop sizes in different meteorological conditions. This is the fundamental aspect that determines the balance between the hazard of drift and the biological usefulness of spray. This paper describes experiments designed to measure the total quantity and spectrum of spray remaining airborne up to 120 m downwind from a single spray line, and to see how this airborne drift varies with meteorological conditions, spray release height and the nature of the underlying crop surface. In order to maximise the different effects between crop surfaces, experiments were carried out over both wheat and fallow fields.

## 2. METHODS AND MATERIALS

The experiments were conducted in the Sudan Gezira – a large irrigated area adjacent to the Blue Nile, with a regular layout of rectangular fields each approx 1300 m by 280 m (36 hectares). Two adjacent fields were selected with their long axes aligned parallel to the prevailing wind direction of 020°. One field contained wheat (variety Giza 155) to a height of approx 0.6 m, and in the later stages of stem extension before ear formation. The other field was fallow, with ploughed

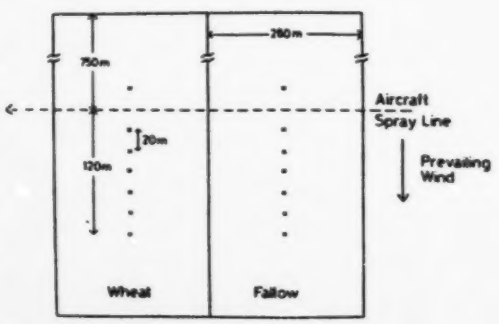



Fig. 1. Schematic diagram of the spray sampling layout.

* This paper is based on a lecture presented to the British Crop Protection Council Symposium on Controlled Droplet Application, Reading, April 1978.

furrows 0.25 m deep (peak-to-trough) aligned cross-wind. The wheat leaf area index was not measured, but information from the Sudan Agricultural Research Council suggests it was in the range 2.0–2.5.

One set of sampling poles was erected in each field, with an upwind fetch of 750 m. The poles were 13 m high and spaced at 20 m intervals downwind to a maximum of 120 m (Fig. 1). The aircraft spray line was perpendicular to the sampling line, and 20 m upwind of the first pole. A further pole was erected 20 m upwind of the spray line. Spray was sampled on vertical cylinders 2 cm in diameter and 20 cm long wrapped with spray sensitive paper.† A chain of seven such cylinders, spaced 2 m apart, hung from each pole. The spray liquid was Dimecron® ULVAIR 250 (a low volatility CIBA-GEIGY formulation containing 25% phosphamidon) with 0.5% w/v fluorescent tracer‡ added to increase drop visibility.

Drop stains were counted and sized under u.v. light using a microscope attached to a Fleming Particle Analyser. True drop diameters were obtained from stain diameters using spread factors determined under field conditions.

Wind and temperature profiles were derived from a 7.5 m mast fitted at six levels with miniature cup anemometers and thermistor probes. The calculated Richardson Number at 3.8 m was used to select those trials conducted under near neutral stability conditions ($|Ri| \leq 0.02$). Wind profiles were well fitted by a logarithmic law with an assumed zero-plane displacement of 0.7 × crop height. The friction velocity, $u_*$, was calculated and used to indicate the strength of the turbulent eddies within the mean airflow. All meteorological parameters were derived separately for the wheat and fallow fields.

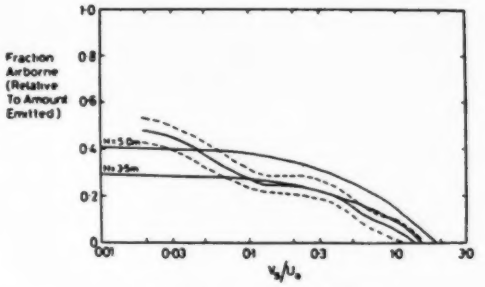
Wind speeds at the spray sampling heights were calculated assuming that the logarithmic wind profile extended above 7.5 m to the highest spray sampling point at 12.5 m. These calculated wind speeds were used to apply corrections to the spray samples to allow for the collection efficiency of the cylinders (May and Clifford, 1967). Instantaneous deviations of wind speed from the measured mean profile generated the greatest experimental error by altering the collection efficiency from the calculated value. For example, a deviation of 0.4 m s$^{-1}$ from a mean wind of 4 m s$^{-1}$ leads to an error of 20% in the calculated number of 20 μm drops. However, this error falls to less than 0.5% for 150 μm drops. The potential size of this source of error required a number of repeated trials to provide a satisfactory mean value for the amount of airborne spray. At each flying height in neutral conditions, a total of 17 trials was carried out over wheat and 8 trials over fallow, i.e. a total of 50 trials.

The spray was produced by a single Micronair AU 3000 rotary atomiser fitted on a boom under the wing of a Pilatus Turbo-Porter aircraft. This aircraft is a single engined, high wing monoplane with a wingspan of 15 m and an unladen weight of 1170 kg. Atomisation by a Micronair occurs when liquid is pumped through a coaxial feed tube into a 15 cm diameter mesh cage which is rotated by 12 cm long impeller blades set at an angle to the incident airflow. With a blade angle of 45°, aircraft speed of 48 m s$^{-1}$ (95 kts) and liquid flowrate of 0.12 l s$^{-1}$ (7 l min$^{-1}$), the Micronair was rotating at 3700 rpm. The aircraft was flown so that the Micronair was either 1.5 or 5 m above the underlying surface, depending on the experiment.

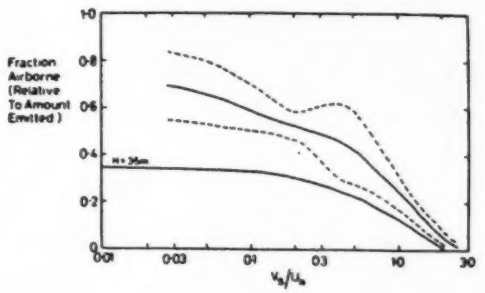
The drop spectrum was measured from the deposit on the first downwind pole, when it was known that no spray had reached the ground in the intervening distance. The mean spectrum from 10 trials had a volume median diameter of 106 ± 3 μm (S.E.). The spectrum was divided into five size classes based on a $\sqrt{2}$ progression covering the range 10–230 μm. The amount of chemical in a given size class passing each pole was calculated by integrating over the seven sampling heights. This was then normalized to the amount of emitted chemical in that size class to yield the fraction of chemical still airborne at the various downwind distances. As both the emitted drop spectrum and the quantity of airborne chemical were calculated in a similar manner, the airborne fraction was independent of systematic errors in both collection efficiency and spread factor.

## 3. RESULTS

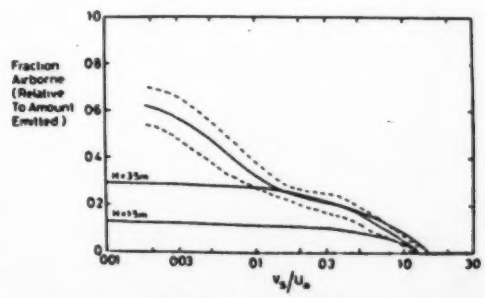
The upper boundary of the spray cloud increased as it drifted downwind until at 120 m it was just grazing the topmost sampling point. Consequently it could be assumed that all the airborne fraction of the cloud was being sampled. The fraction of chemical in each size




(a) Release at 5.0 m over wheat.




(b) Release at 5.0 m over fallow.




(c) Release at 1.5 m over wheat.

Fig. 2. Fraction of spray airborne after 120 m over wheat and fallow surfaces. Wind speeds 2–7 m s$^{-1}$ and $|Ri| \leq 0.02$ at 3.8 m. Experimental mean ± S.E. ≡≡≡≡. Theoretical curve for release at Hm ——.

† Type HN 380, Reed Charts Limited, Clydevale, London.
‡ Neon Red M. F. or Saturn Yellow M. F., Swada (London) Limited.

class that was still airborne at a particular downwind distance was plotted against the ratio of the mean sedimentation velocity, $v_s$, of that size class to the friction velocity $u_*$. This produced graphs similar to Fig. 2(a), which shows the airborne fraction at 120 m downwind over wheat in neutral conditions for a spray release height of 5 m above the crop. The ratio $v_s/u_*$ was chosen for the abscissa to illustrate the relative influence of gravitational settling and turbulent transport on spray dispersal. In neutral conditions over wheat, $u_*$ was related to the mean wind speed, $\bar{u}$, at 4 m by $u_* = 0.097\,\bar{u}_4$. Thus for example, Fig. 2(a) shows that in a wind of 3 m s$^{-1}$ ($u_* \approx 0.3$ m s$^{-1}$) roughly 25% of drops of 45 $\mu$m diameter ($v_s = 0.06$ m s$^{-1}$, $v_s/u_* = 0.2$) remained airborne at 120 m.

Figure 2(a) also shows a theoretical prediction of the airborne fraction for a release height of 5 m above the crop. This prediction was derived from a model by Bache and Sayer (1975) of aerial spray dispersal under turbulent conditions. The model represents both turbulent and gravitational deposition from a Gaussian spray cloud, which was shown to grow linearly during its initial phase of dispersion. The model assumes a constant wind speed with height and quantifies the strength of turbulence by the r.m.s. value of vertical velocity fluctuations. For the present purposes the representative wind speed was taken as that measured at a height of 3.8 m. This was the mean wind speed over the height range covering the spray deposit measurements, and was used irrespective of the height of spray release. The r.m.s. value of vertical velocity fluctuations was approximated by the friction velocity.

### 3.1 *The effect of the aircraft wake*

Although the Bache and Sayer model assumes 100% retention of all drops reaching the surface, it still predicts a larger airborne fraction than that observed. This implies that there must be other factors that act to reduce the airborne fraction below the theoretical minimum. Visual observation of the behaviour of the spray cloud after leaving the atomiser showed that it descended by 1–2 m within about 50 m behind the aircraft, with little obvious distortion of the cloud. This downwash was associated with the roll-up of vortex elements generated by the aircraft wing. Theoretical descriptions of drop trajectories within such vortices have been carried out by Smith (1972) and Trayford and Welch (1972). The effect of the aircraft wake on the subsequent spray dispersal can be accounted for in the current trials by using an effective release height rather than the actual release height. In Fig. 2(a), an effective release height of 3.5 m would bring close agreement between theory and experiment for $v_s/u_* > 0.1$.

### 3.2 *The effect of the underlying surface*

The movement of drops with $v_s/u_* < 0.3$ is determined almost completely by the turbulent airflow, and so they are brought down to the surface with equal efficiency. However, the efficiency with which the surface removes drops from the airflow will depend on the collection efficiencies of the various obstacles intercepted by the drop trajectories. The smaller the drops, the smaller will be these collection efficiencies. Figure 2(a) shows that for drops with $v_s/u_* < 0.1$ (i.e. drops $< 40\,\mu$m in a wind of 4 m s$^{-1}$), the airborne fraction was greater than that predicted assuming complete removal at the surface. It would appear that drops $< 40\,\mu$m were removed from the airflow by the wheat field with less than 100% efficiency. It has been calculated that for drops of 20 $\mu$m the removal efficiency fell to about 75%. The removal efficiency for a given drop size has been defined as the number of spray drops of that size actually removed from the airspace above the crop, relative to the number that would be removed assuming 100% removal efficiency. This definition refers to the bulk removal efficiency of both the crop and ground surfaces as a whole, and does not imply anything about the collection efficiency of individual foliage elements. Due to the grouping of experiments to reduce the variance, the removal efficiency has been averaged over the wind speeds experienced (2–7 m s$^{-1}$).

The effect of spray dispersal in neutral conditions over fallow ground is shown in Fig. 2(b). Here, the lower surface roughness produced a friction velocity that was a smaller fraction of the wind speed ($u_* = 0.079\,\bar{u}_4$) than over wheat, and this change in the intensity of turbulence was included in the dispersal model. The airborne fraction was greater than predicted by theory using an effective release height of 3.5 m, indicating that the removal efficiency of the fallow was less than 100% for all drop sizes.

Table 1 contrasts the removal efficiencies of wheat and fallow fields for different drop sizes, based on the assumption that the removal efficiency of wheat was 100% for drops of 40 $\mu$m and larger.

The difference in removal efficiency between the wheat and fallow surfaces is also illustrated in Fig. 3, which shows the vertical deposit density profiles (summed over all drop sizes) through the spray cloud at 120 m. These are the deposit profiles which would occur on a 100% efficient collector in the airstream. At 12 m above ground the densities over wheat and fallow are similar because the spray drops have travelled directly from the atomiser without encountering the underlying surface. However, closer to the ground (and especially within 3 m) the deposit densities over

Table 1. Bulk removal efficiencies of wheat and fallow fields for various drop sizes (wind speeds 2–7 m s$^{-1}$)

| Drop diameter ($\mu$m) | Wheat (%) | Fallow (%) |
|---|---|---|
| 20 | 75 | 43 |
| 50 | 100 | 60 |
| 90 | 100 | 69 |
| 150 | 100 | 84 |

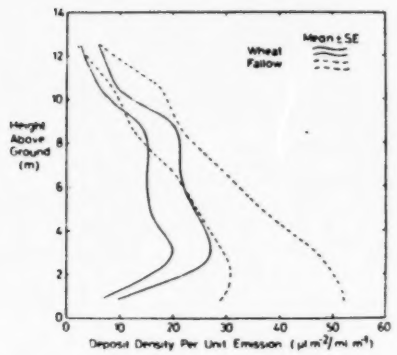



Fig. 3. Profiles of deposit density per unit emission through airborne spray clouds over wheat and fallow surfaces at 120 m downwind. Wind speed 2–7 m s$^{-1}$ and $|Ri| \leq 0.02$ at 3.8 m.

wheat fall rapidly below those over fallow. The total amount of spray airborne over the fallow was about 70% greater than that over wheat.

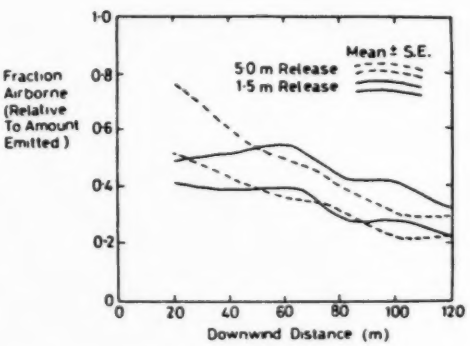
### 3.3 *The interaction of flying height and aircraft wake*

The relation between spray drift and flying height is indicated in Fig. 2(c), which shows the airborne fraction for a spray release height of 1.5 m above wheat. In other respects the experimental conditions were similar to Fig. 2(a). For all drop sizes the airborne fraction at 120 m downwind was greater than the theoretical prediction using the actual release height, except for those drops where gravitational settling started to dominate turbulent dispersal. Much better agreement for $r_s/u_* < 0.2$ was obtained using an effective release height of about 3.5 m. It has been shown (e.g. Dee and Nicholas, 1968; Smith, 1972) that wing-tip vortices generated at a height of one wing span will descend to 0.3 × span and then start rising. However, it would appear that vortices generated very close to the ground (0.18 × span, in this case) also tend to rise, at least initially. This may, in part, be due to viscous limitations on the minimum size of the rolled-up vortex core. The smaller drops are carried up in the rising vortex, thus raising their effective release height.

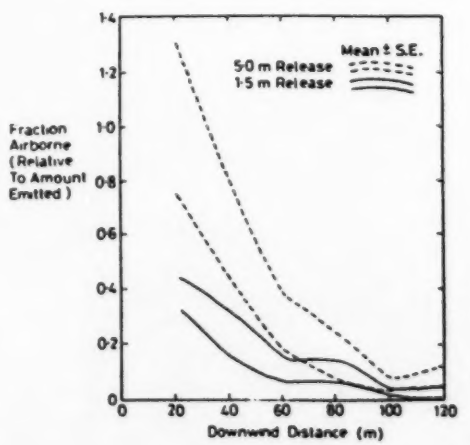
The effect of spray release height on the dispersal of drops of different sizes is further illustrated in Figs. 4(a) and (b), which show the airborne fraction at all downwind distances from the spray line for two categories of $r_s/u_*$. In the typical wind speeds encountered during the experiments these categories correspond to the drop size classes of 30–60 μm and 100–130 μm. It is clear that for the smaller drops, the airborne fraction was not reduced by flying close to the ground. It was only for the bigger drops, with sufficient sedimentation velocity to be less influenced by the vortex flow, that the lower flying height resulted in quicker fall-out. The vortex circulation speeds near the atomiser would appear to be similar to the sedimentation velocity of about an 80 μm drop, i.e. ≈ 0.2 m s$^{-1}$. The atomiser was sited at about 0.15 × span from the aircraft centre line, and the maximum vortex air speeds near the wing tip were 1–2 m s$^{-1}$.

## 4. DISCUSSION AND CONCLUSIONS

Data have been presented on the fraction of an aerial spray that remains airborne at downwind distances up to 120 m as a function of the drop size, the level of turbulence, the characteristics of the underlying surface and the spray release height. The curves in Fig. 2 can be used to predict the fraction of spray still airborne at 120 m downwind from any atomiser for various wind strengths, provided that the initial drop spectrum produced at the atomiser is known. The experimental results were well predicted by a model of spray dispersal in turbulent conditions, once realistic allowance had been made for the change in the effective spray release height by the aircraft wake. This




(a) $r_s/u_* = 0.05$–$0.20$,




(b) $r_s/u_* = 0.6$–$1.0$.

Fig. 4. Variation of airborne spray fraction with downwind distance for two $r_s/u_*$ classes. Wind speeds 2–7 m s$^{-1}$ and $|Ri| \leq 0.02$ at 3.8 m.

agreement occurs despite assumptions in the model of a wind speed that is constant with height and a time dependent diffusion coefficient.

Different airborne fractions were obtained over wheat and fallow surfaces. This emphasises that a realistic assessment of the likely drift or effective swath requires measurements over a field containing the crop of interest. Due to the fact that it had been recently ploughed and the soil was loosely piled, the fallow field in these trials probably had higher removal efficiencies than many surfaces over which drift and swath assessments are often made (airstrip runways, deserts, etc.).

Loss of spray from a field is considered to be reduced by flying closer to the ground. Although generally true, this does not hold when the aircraft is flying very close to the ground. In these circumstances the interaction of the contra-rotating wing tip vortices with the ground causes the aircraft wake to rise. This contrasts with flying 5 m above the ground where the initial movement of the wake is towards the ground. It appears that, at least for a high wing aircraft, no significant reduction in airborne drift for drops less than about 80 $\mu$m is achieved by flying closer than several metres to the ground.

The relation between wind speed and airborne drift is illustrated in Fig. 2(a). For a given drop size with a 100% removal efficiency, there will be no drops remaining airborne beyond 120 m if $v_s/u_*$ is greater than about 1.5. As the wind speed increases ($v_s/u_*$ decreases), so the airborne fraction increases until when $v_s/u_* \approx 0.3$, it levels out at about 0.25. Any further increase in wind speed would only cause a slight rise in the airborne fraction, as indicated by the theoretical curve. (NB: The rise in the experimental curve for $v_s/u_* \leqslant 0.1$ is due to a fall in the removal efficiency of the small drops). Thus for 50 $\mu$m drops with $v_s = 0.07\ \mathrm{m\ s^{-1}}$, very little increase in airborne drift occurs for an increase in wind speed above about $2\ \mathrm{m\ s^{-1}}$ ($u_* \approx 0.2\ \mathrm{m\ s^{-1}}$).

The development of theoretical models of spray dispersal requires a realistic treatment of the interaction of drops with the underlying surface. In the standard Gaussian plume approach, this is usually handled by assuming 100% removal of the plume as it reaches the underlying surface, although recently, Dumbauld *et al.* (1976) have introduced drop size dependent removal efficiencies into their model. An assumption of 100% removal appears reasonable for drops larger than about 50 $\mu$m dispersing over a mature wheat crop. However, measurements of removal efficiencies that are more sensitive to drop size, surface type and wind speed are clearly required.

Even though each experiment in these trials was conducted under nominally similar conditions, there was a high degree of variability between individual results. Although part of this variability could be attributed to minor changes in the experimental conditions, the most significant cause was due to the variability of atmospheric turbulence. A single aircraft spray line is effectively an instantaneous source which experiences only a limited part of the whole spectrum of turbulence. Although in many field trials experiments are repeated in an attempt to reduce the variability, it is usually not known how many experiments are necessary to reduce the standard error to the required fraction of the mean. The significance of the difference between results from two sets of spray application parameters is thus uncertain. In the current series of trials, 8 experiments were required to reduce the standard error of the mean amount of spray airborne at 120 m to within 21% of the mean, while 17 experiments reduced it to 14% of the mean. These figures imply that the coefficient of variation (standard deviation/mean) was constant, with a value of about 0.6.

*Acknowledgements* – The authors wish to thank all members of the CIBA-GEIGY Sudan Project Team, especially the Aviation Group, for their help during the 1-month experiment. Thanks are also due to the Sudan Gezira Board for providing fields for the trials. We are indebted to CIBA-GEIGY Limited for permission to publish this work.

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# Spray Drift from Agricultural Pesticide Applications

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Regina, Saskatchewan

**Pesticide application on the Canadian prairies is primarily by tractor drawn groundrig, with some 5–10% carried out by aircraft. Both types of application have been investigated through field trials to determine the amount of sprayed material leaving the target area at the time of application and the amount of volatilized active ingredient drifting off in the subsequent hour or two following spraying. Variations in this initial off-target drift have been related to meteorological conditions (primarily windspeed), to chemical formulations of the pesticide (generally 2,4-D formulations), and to sprayer parameters such as nozzle type, orientation, and hydraulic pressure. Target deposit masses, off-target deposition, and droplet size distributions of the swath deposits and drift fractions were also measured. Finally, the decrease in drifting droplet mass with increasing downwind travel was investigated under various meteorological conditions. Results to date indicate that some 30–40% of initially deposited butyl ester of 2,4-D evaporates and drifts downwind as vapor in the 2 hr following spraying; the corresponding figure for the octyl ester is 10–15%. Off-target droplet drift at the time of spraying varies between 1 and 8% for ground-rig application, depending on nozzle type and windspeed, and is some 20–35% with aircraft spraying.**

Whenever any agricultural pesticide is applied to a field as a spray from either groundrig or aircraft, there is an initial migration of some of the active ingredient away from the target area. This takes the form of droplet drift at the actual time of the spraying, with the smaller size fraction being preferentially wafted downwind rather than depositing out in the target area. Then following the application, and extending over several hours at least, more pesticide may be carried off downwind through evaporation if the active ingredient is at all volatile. Droplet drift is primarily dependent on the mechanical properties of the sprayer that control dissemination and the size spectrum, while vapor drift depends on the pesticide vapor pressure and the soil surface temperature of the target area; in addition, both will vary with wind speed and atmospheric turbulence conditions. Such drift hazards have been the topic of much research interest over the past years.[1-6]

During the crop season on the Canadian prairies some 20 million acres of land are sprayed with pesticides. At an average application of a half pound per acre, this amounts to around 10 million lb of chemical. Most of the total consists of herbicides, primarily various formulations of 2,4-D. These are generally applied to control weeds in emergent crops or on summerfallow during the period of June 1–July 15 each year. Approximately 90% or more is sprayed from tractor-drawn groundrigs, with aircraft spraying accounting for the remainder. The use of insecticides is more variable and is generally limited to specific areas of outbreaks each year; depending on the insect problem most of this may be applied by aircraft. Again, the time of use is more variable but commonly lies between June 15 and August 15.

The drift from these pesticides beyond the confines of the sprayed fields will consist of both spray droplets and the chemical vapor. If only 1% drifts, the total airborne mass would be 100,000 lb or more of material, mostly 2,4-D. This constitutes a reversal of the classic pollution problem, giving an areal source and a point sink. Specific hazards include susceptible crops, tree shelter belts and groves, and vegetable gardens for herbicides, and bees, wildlife, and fish for insecticides. If use of the chemicals could be made more efficient, drift could be reduced and these hazards ameliorated.

From the middle of the 1960s on, the amount of 2,4-D in the air has been monitored at Regina during the spraying season.[7] For several years additional monitoring stations were operated in Saskatoon, Yorkton, and other locations within the province. The results indicated that on roughly one-third of the days in the 6 week period the concentration over a 24 hr sampling period exceeded 0.1 $\mu g/m^3$ and on a few days each year it exceeded 1 $\mu g/m^3$. There was little or no correlation between the high levels at the various stations. Most of the

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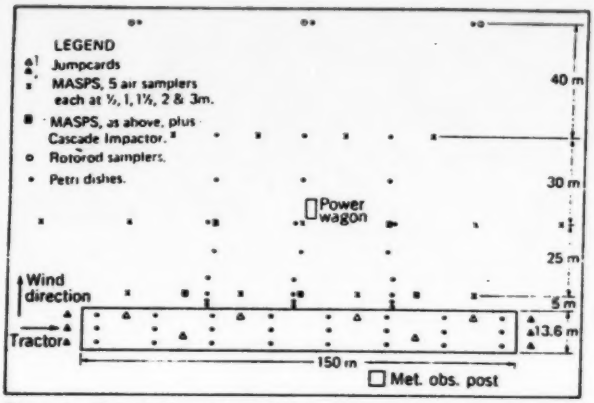


**Figure 1.** Field trial layout, indicating location and type of sampling equipment as described in the text.

chemical was the butyl ester formulation of 2,4-D, with generally lesser amounts of the lower volatile octyl esters also being detected.

That such amounts can be damaging is apparent in the tree foliage condition during July, as well as on occasion in gardens; crop damage is also regularly the subject of insurance claims and litigation. The problem becomes more acute as crop diversification proceeds and larger areas become planted in rapeseed, mustard, and field peas.

In order to estimate the possible downwind hazard of pesticide drift and in particular to recommend ways in which its magnitude may be reduced in practice, it is essential to distinguish between droplet and vapor migration from the target area. A series of field trials was undertaken to ascertain the relative magnitudes of these two drift components for various 2,4-D formulations.[5] These involved the spraying of a swath of ground immediately upwind of a sampling array. Sequential samples taken during and after the spray application provided a measure of the relative amount of initial droplet drift and of the subsequent vapor loss from the swath. Both volatile esters and nonvolatile amines were used.

The results showed that, for 2,4-D butyl ester, some 35% of the applied chemical evaporated from the ground and migrated downwind. For the less volatile octyl formulation the figure was around 12%. Finally, initial droplet drift from the esters as well as from the nonvolatile amine formulation was of the order of 3–5%.[5]

While the vapor was clearly the major contributor to target loss, it could be eliminated merely by phasing out use of the 2,4-D esters, certainly the butyl one. Droplet hazards, even at 3% drift, can still be significant however, as their pickup by plants is more efficient than is that for vapor. It was considered important to determine how this droplet drift fraction might vary with windspeed, and sprayer characteristics, and how rapidly it might diminish with downwind distance. It was also desired to investigate which of the commonly available nozzle and solution combinations might produce the least initial off-swath droplet drift, while at the same time providing a satisfactorily uniform swath deposit.

### Experimental Procedure

The basic field trial layout consisted of a strip of ground (roughly 150 m by 13 m) oriented at right angles to the wind direction and a series of sampling poles and locations downwind of this swath. Surface coverage was typical of that present when regular farm spraying might be carried out. In practice several layouts were staked out at the start of the trial series so that on any given day one of them would be reasonably positioned for the wind on that day. A typical layout is shown in Figure 1. Samplers were placed out to provide a measure of the ground deposit within the swath and downwind of it, and to collect the droplet drift cloud at various heights at several downwind distances. The former consisted of petri dishes 15 cm in diameter and mounted on plywood boards. The latter were small polythene cylinders consisting of sharp edged inlet tube, a ridged, filter disc holder and a critical orifice at the outlet end, set for a flowrate of 10 liters/min. These were mounted every half meter on aluminum poles 3 m in height; the pole served as the suction manifold, to which a pump was attached at the base. A 14 kw power supply, mounted on a trailer was placed in the center of the sampling array, and power lines radiated out from it to each sampling pole. These are designated as MASP's in Figure 1, with the polythene air samplers mounted thereon.

In addition to mass determinations, it was desired to obtain information on the size distribution of the droplets deposited in the swath and of those drifting downwind. For the former samples, small sheets of treated photographic paper were used, on which droplets made sharp edged distinctive stains on landing. Cascade impactors, aspirated at 17 liters/min, provided for size determination of the drifting droplet cloud.

Meteorological observations taken during each trial included wind direction at 2 m height, windspeeds at ½, 1, 2 and 4 m heights, air temperature, temperature difference between ½ and 4 m (to characterize the degree of atmospheric instability), relative humidity and soil surface temperature. All except the last two were continuously recorded, and 5 min averages centered around the actual spraying were taken as the relevant parameter values for each trial. The wind speed at the 2 m height was arbitrarily chosen as the one characterizing the general wind regime. The complete meteorological observation station was located just upwind of the central point of the spray swath.

The groundrig sprayer used in the earlier trials was a standard, tractordrawn farm unit, operating at speeds around 6 km/hr. In the last two years' trials a special twin-boom groundrig was constructed.[8] It permitted the direct comparison of some modification, such as a different spray nozzle, operating pressure, use of a thickening agent, etc., emitted from one of the booms with a standard application technique used in the second boom. As long as the material originating from each could be identified and separately analyzed, the effect of such modification on deposit pattern and droplet drift could be determined directly without the necessity of matching the meteorological parameters for two independent trials.

For the aircraft trials, two different spray planes were used, one a Callair, the other a more modern Cessna Agtruck. Only a single nozzle system was used on each, the standard approved version used in routine operations.

In all trials 2,4-D amine in aqueous solution was used as the basic application; the rate was 55 mg/m$^2$ (8 oz/acre). It was applied as a 0.5 or 1% solution for the groundrig and as a 10% solution for the aircraft. This meant the total emission along the swath of some 100 g of 2,4-D in each trial. The solution volume and hence the amount of 2,4-D applied could be carefully measured with the groundrig, but for the aircraft it had to be estimated from the nozzle delivery rate and flight time. To improve on the sensitivity level available for sample analysis a dye tracer (brilliant sulfoflavine, BSF) was added to the spray solution. For the twin-boom trials the use of a second dye tracer (rhodamine B, RhB) was essential for the partitioning of the sample between the two systems. It was ascertained at the outset that neither dye significantly altered the solution properties or spray characteristics, nor did they interfere with one another at the analysis stage.

The procedure for the field trials followed generally similar lines in all cases. Once the samplers were in place, and flow rates of the aspirated ones checked, the spray solution was mixed and loaded into the tank and the nozzles checked. A set of blank air samplers was aspirated just prior to the trial to provide a correction for possible background contamination levels. For groundrig trials, spraying commenced just prior to the tractor entering the test swath and its speed along the swath, the hydraulic pressure in the tank and the fluid flow-rate to the booms were carefully monitored during the course of the 1–2 min run. The pumps were started at the commencement of spraying, and the air samplers aspirated for a 3 min period, long enough to ensure full passage of the droplet drift cloud. The samplers were then collected and transported back to the laboratory for analysis.

Extraction of the petri dishes, air samplers, and cascade impactor slides was with highly purified ethanol solvent. The samples were then analyzed for dye content in a fluorometer, corrected for blank sample levels and for any photolytic decay of the dye and converted to mass of 2,4-D/sample. For the ground deposit samples, both in the swath and those at various downwind distances, these masses divided by the petri dish area gave deposit densities. Average deposit density and standard deviation within the swath was calculated from the 24 sample dishes present, from which total deposit in grams and swath recovery in percent of mass emitted were readily found. Ground deposits in various downwind strips were analogously determined.

The mass of 2,4-D in each air sample was divided by the sampler flow rate and multiplied by the wind speed for the relevant height to yield a droplet drift density value in mg/m$^2$. When appropriately averaged and multiplied by the vertical and crosswind dimensions the total drift mass and recovery at each downwind distance were obtained.

The mass of dye found for each stage within the cascade impactors permitted a size distribution to be drawn and the volume median diameter to be obtained. For the swath deposits, it was necessary to size microscopically the stains on the paper surface, correct these for spread factor and plot the volume percentages for each size range. This yielded a volume median diameter value for the spray that landed within the swath. The data could also be used as a check on the total deposit mass as found from the petri dish samples.

### Experimental Results

The meteorological conditions for all the trials were generally those that could be expected to pertain to routine farm spraying conditions on the Canadian prairies in June. Air temperatures were between 15°C and 32°C, with soil temperatures some 10–20°C higher, and relative humidities around 30–50%. Most of the trials were carried out under positive lapse rates in midafternoon; a few were conducted in the early morning or evening when the temperature gradient indicated inversion conditions were present. A wide range of wind speeds was involved, from 5 to 35 km/hr so that the behavior of various spray nozzles and sprayer settings and the initial drift they produced could be examined over the range of winds likely to be experienced in farm operations.

For groundrig application the initial drift, i.e., that observed at the sampling line 5 m downwind varied between <0.5% and 8% of the spray emitted, depending on spray nozzle used,

**Table I.** Summary of deposit and initial drift recoveries for various wind speeds and sprayer characteristics

| Trial Type[a] nozzle, and pressure (kPa) | Windspeed at 2 meter height (km/h) | Recoveries per 100g of emission[b] | | | Volume median diameter | |
|---|---|---|---|---|---|---|
| | | Swath deposit + S.D. (g) | Initial off-swath deposit (g) | Initial drift (g) | swath μ | drift μ |
| Groundrig, 8002, 210 | 8.5 | 90 ± 19 | 0.4 | 0.6 | 600 | 13 |
| | 13.7 | 104 ± 17 | 0.9 | 1.2 | 590 | 15 |
| | 22.0 | 83 ± 15 | 1.1 | 1.6 | 650 | 15 |
| Groundrig, 65015, 170 | 9.4 | 106 ± 19 | 0.7 | 0.9 | 600 | 14 |
| | 35.5 | 99 ± 27 | 3.5 | 4.7 | 580 | 20 |
| Groundrig, 650067, 280 | 16.5 | 94 ± 25 | 2.4 | 4.8 | 440 | 15 |
| Groundrig, 8002LP, 100 | 16.4 | 106 ± 22 | 0.7 | 0.6 | 860 | 17 |
| Groundrig, thickener | 16.6 | 107 ± 50 | 0.5 | 0.2 | 1400 | 11 |
| Spracoupe | 3.9 | 93 ± 25 | 3.4 | 5.0 | 240 | 20 |
| | 21.6 | 82 ± 31 | 4.1 | 15.1 | 260 | 10 |
| Aircraft | 7.9 | 61 ± 30 | 6.1 | 14.8 | 280 | 70 |
| | 14.8 | 54 ± 22 | 8.0 | 31.3 | 220 | 100 |

[a] The groundrig sprayer is basically the standard tractor drawn device used by farmers on the Canadian prairies; the Spracoupe is a specialized, wheeled sprayer vehicle; the aircraft results are preliminary average values from tests on both a Callair and Agtruck planes. For the groundrig data, the first number is the designation of the flatfan, Teejet-type nozzle used (i.e. the 8002 is an 80° one, high flowrate, the 650067 is a 65°, low flowrate nozzle etc.) The second number is the hydraulic pressure under which the nozzle was operated (100 kPa = 15 psi). The numbers for each device and windspeed combination are averages of at least four separate trials.

[b] These recovery figures are the following:

(i) swath deposit: for each trial, the average deposit density value of the 24 samples collected in the swath times the swath area and divided by the amount of herbicide emitted (× 100). The S.D. value is the standard deviation of the 24 individual dish values about this mean, again expressed in terms of grams of 2,4-D found per 100 g of emission.

(ii) initial off-swath deposit: the average deposit density found from the 9 samples in the 5 meter wide downwind strip beside the swath (out to the first air sampling line) times the area of this strip and again divided by the amount of herbicide emitted (and again times 100).

(iii) initial drift: the average of all the 35 air sampler amounts found on the 5 meter sampling line converted to mg/m$^2$ of 2,4-D passing this line in the air, multiplied by the cross wind vertical area enclosed by these sampling poles (and multiplied by 100/emission amount as before).

hydraulic pressure, and of course wind speed. Values of this quantity, together with swath deposit and initial off-swath deposit recoveries are given in Table I for some of the nozzle and solution combinations tested. The curves in Figure 2 illustrate how the initial droplet drift fraction was found to vary with wind speed at the 2 m height.

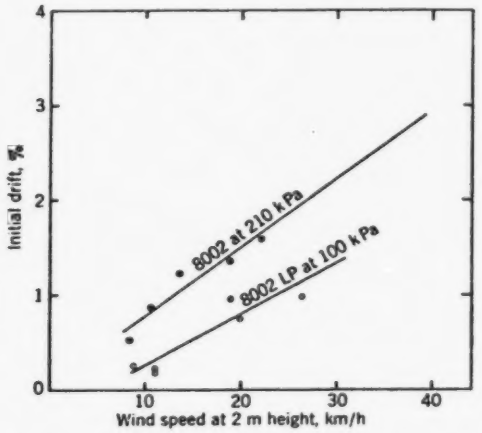


**Figure 2.** Variation of initial droplet drift with wind speed. The solid circles are for an 80° flat fan nozzle (Teejet type 8002) operated at 210 kPa hydraulic pressure, the open circles for a special low pressure version of this nozzle operated at 100 kPa.

Also in Table I is a droplet size measure for the deposit and drift material, as characterized by the volume median diameter.

It is apparent from these last two columns of Table I that the initial off-swath drift from groundrig application consists generally of smaller droplets than that from aircraft spraying, despite the overall smaller sizes produced by the latter. This is understandable inasmuch as the greater release height, and the greater mechanical turbulence accompanying their release from aircraft spraying would tend to enhance the drift tendency over the entire droplet spectrum, compared to that pertaining to ground rig application. It might therefore be expected that the subsequent downwind behavior of the drift cloud would be somewhat different in the two cases. The diminution of the cloud can be determined from the drift densities observed at the air sampling lines 30 and 60 m downwind of the spray swath. The average values, expressed as a fraction of the initial drift density on the 5 m line are plotted in Figure 3. While a separate decay curve would be appropriate to each wind speed value and hence trial, these have been averaged in the figure for simplicity. However, two different rates are shown for the groundrig application, relevant to turbulent (lapse) and stable (inversion) air conditions.

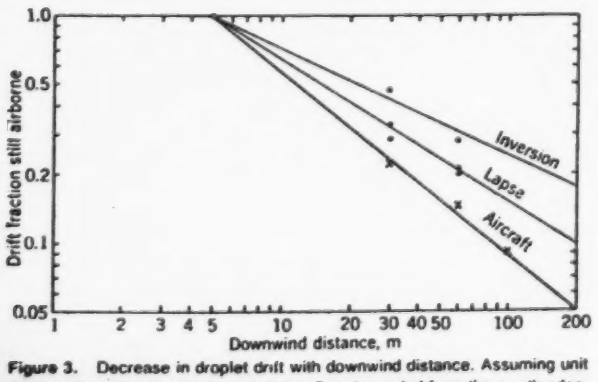


**Figure 3.** Decrease in droplet drift with downwind distance. Assuming unit magnitude drift at the first sampling line 5 m downwind from the swath edge, these curves give the relative drift magnitudes observed from the samplers on the further downwind lines; each point is the average of at least four separate trials.

It is possible to use these drift cloud decay curves to estimate the amount of droplet drift that might be expected to escape from an entire farm field spray operation. The data plotted in Figure 2 are for drift fractions from a single swath; if a second swath had been sprayed immediately upwind of it, drift amounts could be expected at each of the sampling line distances commensurate with the fractional values given in Figure 3 for distances 13 m greater in each case. A third swath further upwind would provide drift amounts as found for distances 26 m out, and so forth. As these drift fractions are purely additive a composite total may be derived; it must, of course, be considered a rough estimate only and conclusions based on it treated with great caution. Table II illustrates this process for the spraying of an entire section (mile square) field. Now for each 1% of drift the average initial drift density will be 2 mg/m$^2$ (assuming the cloud extends only up to 4 m in height and the desired application rate onto the ground is 55 mg/m$^2$). It can be seen that drift density levels exceeding the ground application can be produced in a full field operation, particularly if the drift cloud is confined in its vertical diffusion.

As can be seen from summation of the three recovery values in Table I, it was generally possible to obtain a near total accountancy of the 2,4-D emitted, with the greatest fraction being found in the swath. More important than the total amount found here, however, was its variability; the production of as uniform a deposit pattern as possible is after all the primary goal of the farm sprayer application. The variability was calculated for each trial as the standard deviation of the 24 individual values for the sample dish array. The actual densities could also be plotted and isopleths drawn.

A few trials were carried out with a randomly placed set of sampler dishes; the results gave roughly the same standard deviation for their average as for the regular grid, indicating the latter did provide a reasonable measure of the pattern obtained.

The degree of swath deposit uniformity, as characterized by the standard deviation, was frequently quite different, even under quite similar trial conditions. However, it did not appear to be affected by wind speed unless this was quite high (>30 km/hr), whereupon the standard deviation showed some increase.

The implications of swath pattern variability may be seen from Figure 4, and Table III which is based on it, for the series of trials on the 65° Teejet nozzle. Given a particular type of weed, its surface area and its susceptibility to a particular herbicide, an effective deposit rate (in mg/m$^2$) may be set. If spraying produced a perfectly uniform deposit, this would also be the necessary emission rate for the spray, in mg/m$^2$. The greater the variability, the larger has to be the latter to ensure a desired degree of weed control. Using the curves of Figure 3, it is possible to calculate emission rates that would be needed to achieve 80 and 95% weed control for various levels of susceptibility, as set by assumed deposit rates. As certain factors such as tractor speed, nozzle pressure, and terrain condition were more carefully controlled in the trials than would be possible in routine farm field operations, it must be admitted that even the worst case may not represent the extreme for such operations.

Another feature that appears in Table I regarding the swath standard deviation is that it tended to be much higher for some of the sprayer modifications that effectively reduced drift. This was most noticeable from the twin-boom type of trial, for which the simultaneously obtained samples provided the most direct comparison of drift control and deposit uniformity for any proposed modification. Thus for instance, the considerable improvement in the former factor when thickeners were added to the spray solution has been purchased at the expense of a significant worsening of the latter characteristic. It should be noted that the relatively high swath deposit standard deviations found for Spracoupe and aircraft operations will be reduced through downwind deposition of drifting droplets when multiple swath application takes place.

## Conclusions

It is apparent that, due to the additive nature of the droplet drift coming off successive swaths, even a small fraction of initially drifting material may be hazardous to susceptible plants when herbicides are applied to farm fields. Due to the small size of the drift droplets once the water component has evaporated, ground deposition rates are low, and if vertical diffusion and dilution are moderate, the drift density at the downwind field edge may well exceed the deposit density within the field, even when only 1% initially moves off from each swath.

Over the range of windspeeds commonly encountered during farm spraying operations, the amount of initial, off swath droplet drift increased roughly linearly with the speed,

**Table II.** Estimates of mass flux from the spraying of a section of land at a rate of 55 mg/m² (i.e. 8 oz/acre).[a]

| Relative contribution to drift from: | Downwind field edge | | | 500 m further downwind | | |
|---|---|---|---|---|---|---|
| | Aircraft, lapse | Groundrig, lapse | Groundrig, inversion | Aircraft, lapse | Groundrig, lapse | Groundrig, inversion |
| first swath | 1.0 | 1.0 | 1.0 | 0.1 | 0.2 | 0.3 |
| 2nd–5th swaths | 1.3 | 2.0 | 2.4 | 0.3 | 0.7 | 1.1 |
| 6th–10th swaths | 0.9 | 1.7 | 2.2 | 0.4 | 0.9 | 1.3 |
| 11th–30th swaths | 2.1 | 5.0 | 6.8 | 2.3 | 3.4 | 5.1 |
| 31–120th swaths | 4.4 | 14.7 | 25.4 | 3.5 | 12.5 | 22.3 |
| Total | 9.7 | 24.4 | 37.8 | 3.5 | 17.7 | 30.1 |
| If initial drift is: | 30% | 3% | 3% | | | |
| Average initial drift density (1 swath) to 4 m height (mg/m²):[b] | 60 | 5.4 | 5.4 | | | |
| Total drift (all swaths), averaged to 4 m height (mg/m²): | 580 | 130 | 200 | 330 | 95 | 160 |
| averaged to 10 m height (mg/m²): | 230 | 50 | 80 | 130 | 35 | 65 |

[a] In this table it is assumed that the closest swath to the downwind field edge contributes unit drift at that edge; the relative contribution of each subsequent upwind swath is then found from the decay curves of Figure 3 (eg. the next four swaths contribute in total 1.3 times as much as the first swath in the case of the aircraft, the next 5 together contribute 0.9 times as much as the first, etc.). At 500 m these relative contributions from all swaths are reduced by this further travel according to the relevant decay curves of Figure 3. Thus, the off-field drift from all 120 aircraft swaths, initially 9.7 times that from the closest swath, decreases by nearly half (to 5.5 times the initial, one swath drift) after a further 500 m of downwind travel, etc.

[b] These figures are found from multiplying the swath deposit density (50–60 mg/m²) by the drift percentages in the above row and by the ratio of swath width to drift cloud height (16m/4m for aircraft, 13 m/4 m for groundrig). The figures in the last two rows are then obtained by multiplying these one-swath drift amounts by the total contributions of all swaths as found above (eg. 9.7, 24.4 etc.). Both the initial drift density and the total drift figures here refer to the mass of chemical passing through a unit vertical cross-section at right angles to the wind direction.

**Table III.** Emission rates of herbicide necessary to ensure that at least 80 or 95% of the area sprayed receives enough deposit to control the weeds, given three different swath variability levels.[a]

| Assumed effective deposit density (mg/m²) | Fraction of area to receive at least amount in previous column (%) | Necessary emission rate (mg/m²) Average | Best case | Worst case |
|---|---|---|---|---|
| 20 | 80 | 28 | 23 | 40 |
| 20 | 95 | 49 | 25 | 120 |
| 35 | 80 | 47 | 40 | 75 |
| 35 | 95 | 85 | 45 | 200 |

[a] Here it is assumed that either 20 or 35 mg/m² is sufficient herbicide for weed control and that one wishes to ensure that either 80 or 95% of the weeds receive at least this amount. The emission rates necessary to achieve these various levels are then found from one of the three lines shown in Figure 4. For instance, if the sprayer is behaving as shown by the "average" curve of Figure 4, an application rate of 28 mg/m² will ensure that 80% of the area receives at least 20 mg/m²; on the other hand if it was behaving more erratically and producing a very uneven deposit as illustrated by the "worst" case, it would be necessary to apply the chemical at a rate of 40 mg/m² to ensure that 80% of the area received at least 20 mg/m², or at a rate of 120 mg/m² if one wanted 95% effective coverage and control.

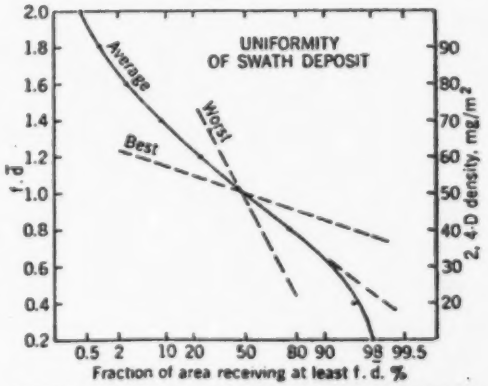


**Figure 4.** Variation of swath deposit uniformity with standard deviation of the sampler array. Based on the standard deviation about the mean deposit density as found from the 24 petri dish samples, it is possible to calculate what fraction of the test swath area received at least *f* times the average density, and what this fraction means in terms of actual deposit density. The "average" curve is the mean of 14 separate trial results, one of which is represented by the "best" curve and one by the "worst".

at least for groundrig application. This was not obvious for the initial droplet drift from aircraft spraying but became established at greater downwind distances. Clearly, spraying under the lightest winds possible is advisable, particularly when near susceptible plants, trees, and crops. Spraying under inversion conditions, when upward dilution of the drift cloud is much reduced, is disadvantageous, except insofar as the winds may be very light at such times.

Tests on various modifications to groundrig sprayers indicated that reducing the hydraulic pressure, applying more total solution volume, using thickeners, or low pressure nozzles, resulted in every case in a reduced level of initial drift. All achieved this through a coarsening of the droplet size spectrum, with a resultant reduction in the volume of small droplets produced. This improvement, however, was frequently accompanied by an unacceptable worsening of the swath deposit uniformity. In one or two of the modifications, reduction in the initial droplet drift fraction could be attributed as well to a lowered boom height. Again this might be accompanied by a greater variability of the pattern, at least over rough terrain, or where boom whiplash occurred.

In surveying these results of drift control modifications it appears that a more promising approach would be to work towards improving the homogeneity of the swath deposit.[8] If this were achieved, the chemical emission rate that is necessary to produce a desired level of weed control could be reduced. This in turn would result in a decrease of the off-swath drift for any given combination of sprayer parameters.

It should be noted that while these studies have been carried out on 2,4-D, the findings are basically applicable to any herbicide. The physical properties of the solution, rather than the biological effects of the active ingredient, are involved and once known, may be used to identify any divergence in quantitative values of deposit and drift features. The same generalization may be made for the consideration of insecticide application, except for the proviso that the desired interaction of droplet and target will be different.


### Acknowledgments

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# Criteria for Minimizing Drift Residues on Crops Downwind from Aerial Applications

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MEMBER ASAE MEMBER ASAE

DRIFTING of chemical sprays is potentially a hazard in diversified farming areas whenever injurious pesticides are applied by agricultural aircraft. Nevertheless, the risk of injury or contamination to nearby crops can be minimized if proper criteria are used in selecting the various application parameters.

Research studies to determine drift residue characteristics and application techniques that will result in minimum residues from aerial applications were initiated by the Agricultural Engineering Department, University of California, Davis, in 1960. Since that date, numerous progress reports have been published. To name a few, (Yates et al. 1963, 1966, 1967) contain a bibliography of previous literature reviews, a detailed description of experimental procedures and a summary of research results through 1965. Butler et al. (1969) and Holmsen et al. (1967) reported results of drift tests conducted during 1966. Both papers include experimental data on the effectiveness of certain drift control agents that are available commercially. This paper discusses the principal results and analyses of the drift tests that were conducted in 1966. Basically, the tests extend the drift residue information over a wider range of conditions and identify some of the most important criteria for minimizing drift residues from aerial applications.

## EXPERIMENTAL TECHNIQUES

The experimental design used in the field tests to measure drift fallout characteristics was similar to the design of previous drift experiments (Yates et al. 1966). Briefly, Fig. 1 illustrates the field layout for the tests. As shown, alfalfa was grown in the SW, NW, and NE quarter sections, and sugar beets in the SE quarter. This site included a maximum drift line of 4612 ft for the prevailing wind direction, a substantial improvement over the approximately 2640-ft maximum provided by the previous areas. An irrigation ditch with banks approximately 2 ft above the ground level was located along the N-S line through the center of the sprayed area. Later tests were conducted in the section immediately south of the first area. At this location the block of alfalfa was in the NE and SE quarters of the section. With the prevailing wind direction the maximum length of the drift line was 2640 ft. The field was smooth, without obstructions along the spray line or downwind along the sampling line.

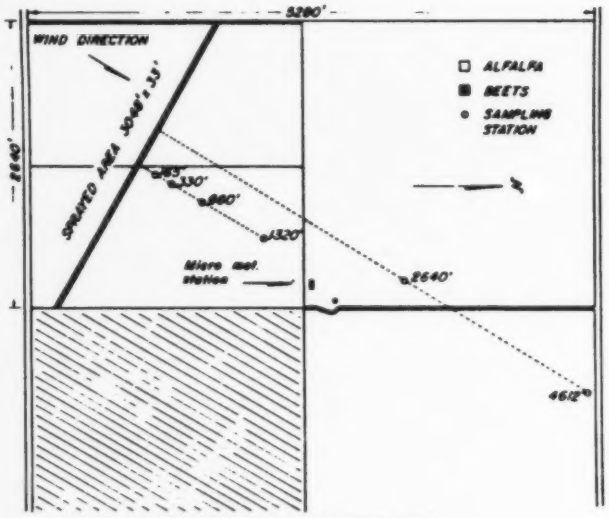


FIG. 1 Map of field layout for 1966 drift tests. Wallace Ranch near Davis, Calif.

The spray applications were made with modified Stearman and Navy N3N aircraft. Both are similar types of single-engine biplane aircraft, each equipped with a P&W R-985 450-hp engine. Each test consisted of seven to eight replicate passes over the single marked course. Each spray mixture contained a fluorescent tracer or a pesticide material or both. Sampling stations were spaced at logarithmic intervals along the drift line. The fluorescent deposits on Mylar sample sheets were analyzed with a Turner Model 110 (G. K. Turner associates) fluorometer (Yates and Akesson 1963), and the pesticide residues on the alfalfa were analyzed with an Aerograph Hi-Fy (Wilkens Instrument Company) Model 600D gas chromatograph with an electron-capture detector.

Micrometeorological measurements were taken at a point approximately 1750 ft downwind from the flight path at the first test site, and approximately 2750 ft. from the flight path at the second test site. Temperature and wind velocity were measured continuously at elevations of 48, 32, 16, and 8 ft. Also measured at the 8-ft elevation were wind direction and humidity.

The wind velocity and direction measurements at 8 ft were used to calculate the spray trajectories (Yates et al. 1966) for each pass of the aircraft. The drift deposit information for a given station was omitted if any of the trajectories missed that station. In addition, the trajectory information was used to determine the precise distance the spray traveled to each sampling station. Also,

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TABLE 1. APPLICATION CONDITIONS FOR 1966 TESTS.

| Test | Nozzles type orientation | Application rate, gpa | Formulation percent oil phase | Temp. at 8 ft deg F | Temp. diff. $T_{32}-T_8$ deg F | Wind speed, mph 8 ft | 16 ft | 32 ft | S. R. |
|---|---|---|---|---|---|---|---|---|---|
| May 66, A | D6-46, back | 5.6 | 7.0 | 68 | 0.50 | 16.0 | 19.0 | 21.9 | 0.04 |
| May 66, C | D6-46, back | 6.7 | 2.8 | 66 | 0.54 | 13.9 | 16.1 | 19.0 | 0.06 |
| June 66, B | D6-46, back | 6.5 | 2.8 | 76 | 0.07 | 12.5 | 15.3 | 17:7 | 0.01 |
| June 66, C | D6-46, back | 6.5 | 2.8 | 71 | 0.64 | 12.7 | 15.4 | 17.7 | 0.08 |
| July 66, D | D6-46, back | 7.1 | 2.8 | 79 | 0.18 | 8.4 | 10.0 | 12.0 | 0.05 |
| Oct. 66, A | D6-46, back | 5.3 | 2.8 | 69 | -0.01 | 13.3 | 14.9 | 16.5 | -0.01 |
| Oct. 66, B | D6-46, back | 6.7 | 2.8 | 66 | 3.85 | 4.2 | 5.8 | 7.7 | 3.23 |
| July 66, A | D6-45, down | 3.65 | 2.8 | 83 | 1.12 | 7.7 | 6.5 | 10.8 | 0.74 |
| July 66, B | D6-45, down | 3.25 | 2.8 | 78 | 1.94 | 7.1 | 8.6 | 10.4 | 0.73 |
| July 66, C | D6-45, down | 4.33 | 10.0 | 75 | 1.04 | 9.9 | 11.9 | 13.9 | 0.20 |
| June 66, D | D6-46, back | 6.5 | 100 | 67 | 0.70 | 10.9 | 13.3 | 15.4 | 0.11 |

the meteorological conditions for each test were averaged over the time interval established from the trajectory calculations.

All residue data were normalized to a standard set of conditions to facilitate comparison between runs. The residues were corrected to an equivalent of micrograms per sq ft per pass and for an equivalent application of 1 lb of active material per acre. Also applied to the residue values were appropriate corrections for wind-direction deviations and fluorescent degradations.

## SPRAY TESTS

Table 1 gives the basic application conditions for eleven tests. The experiments were designed to obtain additional information on the effects on drift residue characteristics of microweather conditions, atomization, and formulation parameters.

In regard to microweather factors, previous experiments (Yates et al. 1967) have been conducted over a wide range of temperature gradients but covered only a limited range of wind velocities, 3 to 9.5 mph. Thus, one objective of this program was to obtain information on drift during higher wind velocities. As shown in Table 1, the wind velocity during the first group of 7 tests ranged from 16.0 to 4.2 mph, being in excess of 10 mph during five of the tests. All applications in the first group were made with Spraying Systems D6-46 nozzles directed back with a pressure of 30 to 40 psi and an air speed of 100 mph. This type of hollow-cone nozzle system is used commonly for applications of insecticides at the rate of 5 to 10 gal per acre, with a VMD (volume median diameter) drop size of 450 microns.

The second group of tests covered in Table 1 was conducted to determine the effect of atomization. Previous tests have shown the general drift patterns from atomization equipment typically used for 5 to 10 gal per acre and for ULV applications of 0.1 gal per acre. In July, 1966, three applications were applied with Spraying Systems D6-45 nozzles directed down with a pressure of 38 to 41 psi and at an air speed of 100 MPH. This atomization system was designed to produce a smaller droplet spectrum (of about 175 microns VMD) than that used in the first group of tests. It was of interest because it is used commonly for applications of insecticides at the rate of 1 to 5 gal per acre.

The last test listed in the table was designed to demonstrate the effect on drift characteristics of the amount of oil phase in the spray formulation. Previous experiments (Yates et al. 1966) indicated a trend toward increased residues as the oil phase of a standard O/W emulsion increased from 1.8 to 10 percent. To determine the maximum effect of this parameter, a single test was conducted with a spray containing 140 gal diesel oil and 3 lb Fluorol 7GA oil-soluble fluorescent dye (General Aniline and Film Corp.).

The standard 2.8 percent (by volume) O/W emulsion used in the other tests consisted of 15 lb xylene, 15 lb H-stock summer oil (Chevron Chem. Corp.), 1.75 lb Triton X-100 emulsifier (Rohm and Haas Co.), 4.0 lb Brilliant Sulpho Flavine (General Aniline and Film Corp.) fluorescent dye, and 145.8 gal of water.

## DRIFT DEPOSITS FROM SINGLE-LINE SOURCE EXPERIMENTS

Results of the residue data for each test were analyzed statistically as presented by Yates et al. (1967). Briefly, an IBM 7044 computer was used to calculate the best "least-squares" second-degree polynomial regression of the relationship between the residues and the distance downwind. The general form of the regression was

$$\log D = b_0 + b_1 (\log d) + b_2 (\log d)^2$$

where D is the deposit on Mylar in micrograms per sq ft.

$b_0, b_1, b_2$ are regression coefficients

d is the distance downwind in feet.

Table 2 lists the regression coefficients for some of the single drift tests and some selected combinations of several tests conducted under similar condi-

TABLE 2. REGRESSION COEFFICIENTS FOR 1966 DRIFT TESTS

WHERE: $\log D = b_0 + b_1 (\log d) + b_2 (\log d)^2$

| Test | $b_0$ | $b_1$ | $b_2$ |
|---|---|---|---|
| Comb. 6 tests: May 66 A, C June 66 B, C, July 66 D Oct 66 A. | 10.511 | -5.0283 | 0.52144 |
| Oct. 66 A | 7.9869 | -3.4193 | 0.27114 |
| Oct. 66 B | 10.131 | -5.7378 | 0.8674 |
| Comb. 3 tests July 66 A, B, C | 8.3666 | -3.6470 | 0.36409 |
| June 66 C | 12.064 | -6.1756 | 0.7397 |
| June 66 D | 3.6034 | 0.11049 | -0.27114 |

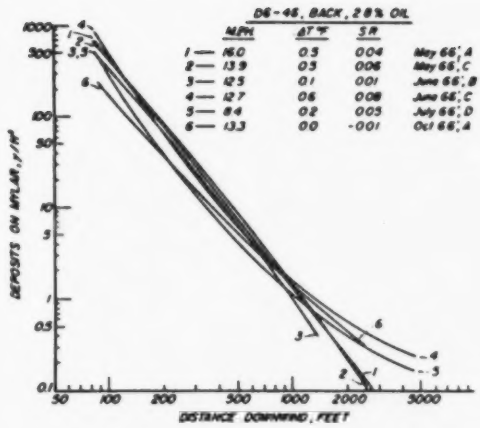


FIG. 2 Regression lines for tests during nearly neutral atmospheric conditions.

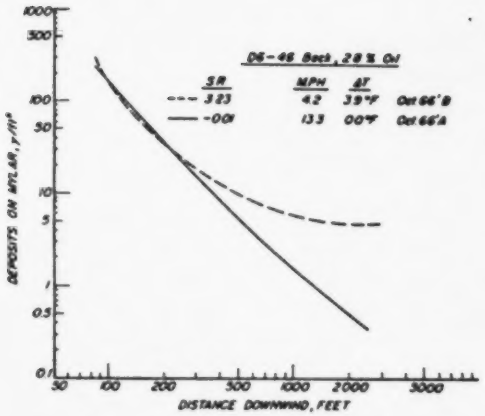


FIG. 3 Effect of stability ratio on drift deposits.

tions. The 99 percent confidence limits were calculated to indicate the accuracy of each regression equation. Thus the use of regression equations and confidence limits provided a reliable method of comparing drift residues from different experiments and was a useful analytical tool for the summation calculations discussed in the last section.

## RESULTS AND DISCUSSION OF THE REGRESSION ANALYSIS OF THE 1966 TESTS

### Micrometeoroligical Conditions

Previous drift experiments (Yates et al. 1966) have shown that micrometeorological conditions are one of the most important parameters influencing drift residues. Further, it has been shown that the Stability Ratio, S.R., (Munn 1966) is a convenient index of atmospheric conditions related directly to drift residues. The Stability Ratio was calculated as follows:

$$\text{Stability Ratio} = \text{S.R.} = \frac{T_{32} - T_8}{\bar{u}_{16}^2} \; 10^5$$

where

$T_{32}$ is temperature at 32 ft in deg C
$T_8$ is temperature at 8 ft in deg C
$\bar{u}_{16}$ is the average wind velocity at 16 ft in cm per sec

The drift tests from previous years have been grouped into the following general categories of atmospheric stability:

| | | |
|---|---|---|
| Unstable | S.R. | -1.7 to -0.1 |
| Neutral | S.R. | -0.1 to 0.1 |
| Stable | S.R. | 0.1 to 1.2 |
| Very stable | S.R. | 1.2 to 4.9 |

Results have shown that the drift regression curves for different S.R.'s are generally divergent, with differences in residues becoming greater with distance. At the more distant stations the drift residues show a progressive increase in residues as the Stability Ratio increases. Thus, the S.R. is an important index for estimating drift residues (Yates et al. 1967).

The first group of seven tests in Table 1 were evaluated to determine whether the S.R. was a satisfactory index that would relate atmospheric conditions to the type of drift residue patterns during high wind velocities. The 1966 tests provided drift data during five tests with winds in excess of 10 mph, whereas for previous tests the maximum velocity was 9.5 mph. The S.R.'s for the 1966 tests are shown in Table 1.

During the first six tests the velocity ranged from 8.4 to 16.0 mph and the temperature gradient ranged from -0.01 to 0.54 F. however, atmospheric stability was nearly neutral, with the S.R. ranging from -0.01 to 0.08. It should be noted that the S.R. approaches zero with a high wind velocity because the turbulence associated with high wind tends to prevent temperature stratification, keeping the temperature gradient low. In addition, since the velocity term in the denominator of the S.R. is squared, the ratio would likewise tend to produce an S.R. near zero.

Since the S.R. was nearly the same for the first six tests, it was of interest to see whether the corresponding drift residues were similar. Fig. 2 plots the second-degree polynomial regression curves of the drift residues versus the distance downwind for the six tests. All of the curves indicate similar drift patterns. Also, previous tests under neutral conditions but lower wind velocities (Yates et al. 1967) produced a similar nearly straight-line plot on log-log paper. The small departures from a straight line at both ends of the curves in Fig. 2 were not attributed to wind velocity, since the 16-mph tests produced about the straightest line and the deviations from the other tests did not appear to have any particular trend but flared in both directions. The variations at the closer stations were attributed to variations in the flight height of the aircraft. It was noticed that the residues 82 ft downwind were somewhat higher than the results from previous tests near Bakersfield. Again, this was attributed to the fact that in Bakersfield the height of flight was very low, with the aircraft wheels running in the alfalfa to a maximum of 2-3 ft above the crop. At Davis all the flights were slightly higher, with the aircraft flying 2 to 5 ft above the alfalfa both because of turbulent winds and the irrigation ditch at the center of the first test area in 1966. Unfortunately, the ditch caused the pilot to increase his elevation at the point nearest the sampling stations. Thus, flight height appears to be a factor affecting residues at the close stations. Also an extremely low flight path is difficult to maintain during turbulent, windy conditions.

Fig. 3 dramatically illustrates the important effect of S.R. on the type of drift residue pattern. The two tests in October directly compare drift residues under very stable with neutral atmospheric conditions. At 1/2 mile downwind the residues were over 13 times greater during very stable conditions as compared to neutral conditions. This same effect was noted in previous experiments. Fig. 3 verifies the point that at the close stations the residue level does not seem to be related to wind velocity. As shown, the two tests in October were during winds of 4.5 and 13 mph, yet the residues were similar at the close stations. The initial residues at 82 ft

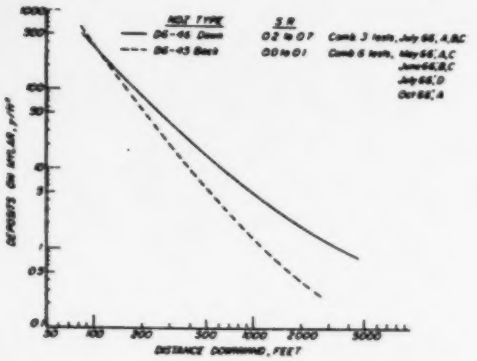

FIG. 4 Effect of spray atomization on drift deposits.

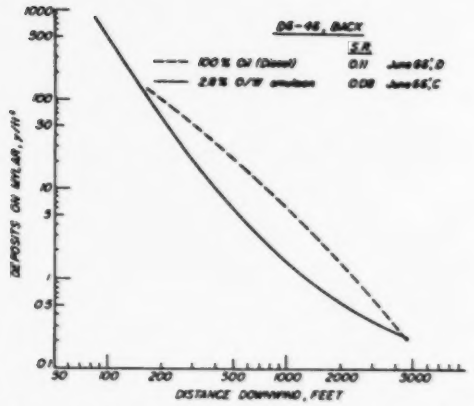

FIG. 5 Effect of nonvolatile oil content on drift deposits.

were somewhat lower than the results at the first 1966 locations. This may be because the flight height was somewhat lower.

### Atomization

Atomization (particle size) is another important factor affecting the drift of material released from agricultural aircraft. For instance, tests in 1965 (Yates et al. 1967) have shown that a change in the orientation of D6-46 nozzles from back to down reduced the drop size sufficiently (from 450 to 280 microns VMD) to increase the residues at 1000 ft by a factor of 2.0.

Fig. 4 compares 1966 data on drift from applications with D6-45 nozzles directed down and with D6-46 nozzles directed back. Three tests in July 1966 (Table 1) were conducted to evaluate residue characteristics with the D6-45 nozzles. The three applications were during similar atmospheric conditions, S.R. 0.2 to 0.7, and the regression curves of the drift residues for each test were similar. Consequently the data from the three tests were combined for calculation of a more representative single-regression curve. For comparison, the first six tests (Table 1) with D6-46 nozzles directed back were combined into a single composite regression. The curves indicated an expected divergence of drift residues. At 1/2 mile downwind the residue was 5.5 times greater with the finer atomization. The two regressions were utilized for the prediction of residues under typical application conditions, discussed in the last section of this paper.

### Oil Content

Another physical factor affecting drift characteristics is the percent of nonvolatile material in the spray mixture. In a water-diluted formulation the particle size of the drift cloud is reduced by evaporation to the volume equivalent of the nonvolatile fraction. For a 2.8 percent O/W emulsion, the particles would be reduced to 0.3 of their original diameter. Thus, the amount of nonvolatile material can affect the drift residue pattern significantly, and also the amount of airborne material that may be carried out of the immediate area.

Previous drift results have shown a trend toward increased residues with an increase in oil content. It should be noted that the tests were limited to a range of oil content from 1.8 to 10 percent and that the maximum distance of reliable residues was restricted to approximately 1000 ft. Two tests in June 1966 provided drift residue data from applications with an oil content up to 100 percent and reliable data as far as 4600 ft downwind. Fig. 5 shows drift residues from one application with 100 percent diesel oil and one with a 2.8 percent O/W emlusion. Both tests were under similar atmospheric conditions, S.R.'s of 0.08 and 0.11, and with the same atomization equipment, D6-46 nozzles directed back which would produce approximately the same initial drop size. The drift pattern from the diesel-oil application was noticeably different, producing a convex curve on log-log paper, compared with the concave curves typical for low-oil-content formulations applied under slightly stable weather conditions. A comparison of the curves (Fig. 5) indicates that the ratio of drift residues from the 100 percent-oil application to the 2.8 percent emulsion increased rapidly to a maximum of over 4.0 times between 500 to 1000 ft downwind. Beyond 1000 ft the ratio decreased, approaching 1.0 (the same residue level at 4600 ft. Thus, the drift residues were higher for the high-oil-content formulation up to 4600 ft, but the trend indicates that there is a possibility of the ratio reversing beyond 4600 ft. Additional tests are needed to establish any general relationships, since the effect of oil content may be interrelated with the other parameters of S.R. and atomization.

## PREDICTION OF PESTICIDE RESIDUES

Methods of predicting pesticide residues for typical field applications have been described in detail (Yates et al. 1967). Briefly, the technique involves an estimation of the deposits on Mylar sheets from the desired drift regression line or its upper 99 percent confidence limit. The next step involves converting the residue on Mylar into an equivalent residue on the crop in terms of ppm. Again, the corelation involves a regression equation, and, if desired, an upper 99 percent confidence limit may be used. Finally, the total cumulative residue at a given point downwind from a typical application can be estimated by summing up the residues contributed by each swath at its appropriate distance.

**1 Correlation of deposits on Mylar with residues on green alfalfa**— Previous research data (Yates et al. 1967) indicated a straight-line correlation between the log values of residues on Mylar sheets and the coresponding log values of pesticide residues on green alfalfa in ppm. A regression was calculated based upon the following applications of pesticides and fluorescent tracers: Tedion-BSF in June 1961, Tedion-BSF in August 1961, and Methoxychlor-BSF in September 1964. One additional test was conducted with Methoxychlor-BSF in June 1966.

The straight-line regression for all available data points was:

$$\log P = -2.4544 + 1.00 \log D$$

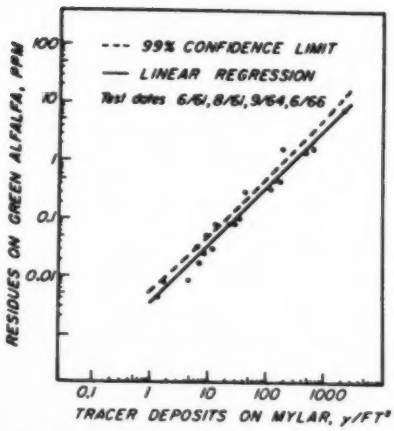


FIG. 6 Correlation of tracer deposits on Mylar sheets with pesticide residues on green alfalfa.

where

P = pesticide residue on green alfalfa in ppm

D = deposit on Mylar sheets in micrograms per sq ft.

The slope of 1.00 indicates a constant proportionality between the fluorescent residues on Mylar and pesticide residues on green alfalfa. The equation was left in the above form to facilitate summation calculations based upon the upper 99 percent confidence limit. Fig. 6 illustrates the regression line, along with the data points and the upper 99 percent confidence limit. It should be pointed out that the confidence limit was based upon the 99 percent probability that the average value would not exceed the confidence limit. The confidence limit which includes 99 percent of the individual points would be much higher. It was felt that the confidence limit for the average value was a more realistic value to use since most legal claims would require more than a single analysis to establish the pesticide residue.

**2 Cumulative pesticide residues**—Predictions of the cumulative residues for the 1966 tests are shown in Table 3 as the summation calculations for a simulated field application of 20 swaths. Calculations were based upon a wind perpendicular to the flight line and swaths progressing across the treated area at 33-ft intervals. Thus, with a field length of 1/4 mile, a 20-swath application would represent a 20-acre treatment. Table 2 includes results of summation calculations based upon both the regression estimate and the upper 99 percent confidence limit of the average values for each equation. Since the farmer would normally be concerned with the residue at the time of sale, the values presented in Table 3 are in terms of ppm on dry alfalfa hay. The loss of moisture during field curing of alfalfa, from approximately 79 percent to 16 percent moisture w.b., would increase the apparent residue in ppm approximately fourfold. Thus, all values from the summation program were multiplied by 4.0 to express the equivalent residue in terms of ppm on dry alfalfa hay. The tabulated values are representative of a stable compound and a drift occurring immediately prior to harvest. For some chemicals there may be an apparent loss or degradation during curing or due to a time lapse prior to harvest. If the degradation characteristics of the chemical are known, the appropriate factors could be applied to the tabulated values. Thus, Table 2 contains basic information which can be used to establish certain operational criteria for minimizing the fallout or drift from aerial applications. The regression values provide the best estimate of the residues. However, the estimates based upon the upper 99 percent confidence limit will be used in the following discussion since this estimate will indicate conditions with a high degree of assurance, 99 percent probability, that the average drift residues for future applications under similar conditions will not exceed the estimated residue.

TABLE 3. CUMULATIVE RESIDUES ON DRY ALFALFA, PPM 20 SWATHS, 20 ACRES ON A 1/4 MILE RUN. 1 lb PESTICIDE PER ACRE.

| Distance downwind, ft | | 83 | 149 | 314 | 644 | 1304 | 2624 | 3944 |
|---|---|---|---|---|---|---|---|---|
| Combination 6 tests, S.R. −0.1 to 0.1 | Regres. | 11.44 | 4.20 | 1.30 | 0.44 | 0.16 | 0.06 | 0.04 |
| 2.8 - 7% oil, D6-46 back | Upper 99% c.l. | 18.70 | 6.26 | 2.03 | 0.76 | 0.30 | 0.14 | 0.10 |
| Oct. 66 A, S.R. −0.01 | Regres. | 7.00 | 3.30 | 1.26 | 0.49 | 0.18 | | |
| 2.8% oil, D6-46 back | Upper 99% c.l. | 12.90 | 5.66 | 2.29 | 0.94 | 0.40 | | |
| Oct. 66 B, S.R. 3.23 | Regress. | 6.77 | 3.97 | 2.31 | 1.57 | 1.27 | | |
| 2.8% oil, D6-46 back | Upper 99% c.l. | 10.47 | 5.94 | 3.55 | 2.44 | 2.08 | | |
| July 66 A, B, C, S.R. 0.2 to 0.7 | Regres. | 15.34 | 7.99 | 3.54 | 1.60 | 0.74 | 0.35 | 0.24 |
| 2.8% to 10% oil, D6-45 down | Upper 99% c.l. | 23.79 | 11.56 | 5.13 | 2.43 | 1.18 | 0.61 | 0.45 |
| June 66 C, S.R. 0.08 | Regres. | 14.51 | 4.87 | 1.45 | 0.52 | 0.21 | 0.10 | 0.07 |
| 2.8% oil, D6-46 back | Upper 99% c.l. | 32.55 | 9.05 | 2.79 | 1.08 | 0.46 | 0.24 | 0.20 |
| June 66 D, S.R. 0.11 | Regres. | 17.38 | 11.11 | 5.31 | 2.11 | 0.68 | 0.18 | 0.07 |
| 100% oil, D6-46 back | Upper 99% c.l. | 42.07 | 21.22 | 9.36 | 3.89 | 1.33 | 0.40 | 0.20 |

### Microweather Conditions

The first three sets of data in Table 3 indicate the estimates of drift residues under various weather conditions. The applications were with D6-46 nozzles directed back, 5-7 gal per acre, 2.8 to 7 percent O/W emulsions, and an equivalent application of 1 lb of active chemical per acre. In 1966 California had a residue tolerance of 0.5 ppm on DDT produce sold for livestock feeds such as dry alfalfa hay. Thus, based on these data, this 20-swath application of DDT would not create a significant hazard to an alfalfa field 1/4 mile downwind.

The October A and October B tests (Table 3) illustrate a direct comparison of residues under neutral and very stable (temperature inversion) conditions. A comparison of residues at 1/4 mile emphasizes the hazard of the very stable condition. The neutral condition results in residues well below 0.5 ppm (99 percent c.l.), whereas the residue was 2.0 ppm (99 percent c.l.) for the very stable

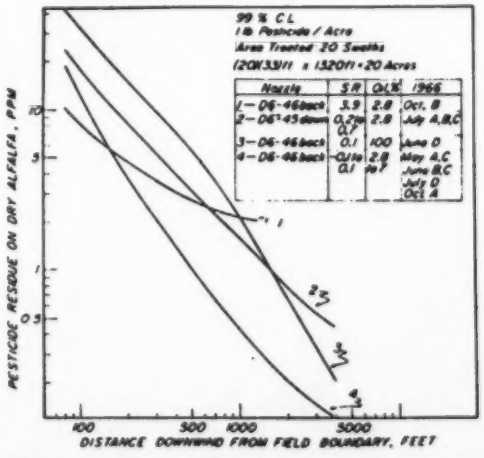


FIG. 7 Cumulative residues for various types of applications.

condition. Fig. 7 illustrates the trend of drift residues under neutral conditions (line 4) and the very stable condition (line 1). The curves again emphasize the importance of avoiding applications during very stable conditions. As previously noted, the high wind velocities may be desirable because they ensure nearly neutral stability conditions as well as dilluting airborne particles over a greater distance. The resulting residues during 8 to 16 mph winds, (line 4) are well below 0.5 ppm at 1/4 mile. It should be noted that the residues at the close stations were significantly higher than in previous tests at Bakersfield. However, the cumulative residues beyond 650 ft were similar and the residues for a 20-swath application and neutral conditions were below 0.5 ppm at 1/4 mile in both series of tests.

### Atomization

Table 3 shows the cumulative residues from the composite data of three applications (A, B, and C) in July 1966. The applications were with D6-45 nozzles applying a 2.8 percent O/W emulsion at 3 to 4 gal per acre. The finer atomization (175 microns VMD) produced a very significant drift hazard. At 1/2 mile the 99 percent c.l. for the 20-swath application was over 0.5 ppm, approximately 2.5 times as great as the 99 percent c.l. for the June C application with D6-46 nozzles. Tests with the D6-45 nozzles were during slightly higher stability conditions, S.R. 0.2 to 0.7 compared to an S.R. of 0.08 during the D6-46 test. Thus a small part of the increased residues for these tests could be attributed to increased stability. Curve 2 in Fig. 7 reveals the important fact that the slope of the residue curve is quite flat, so a significant residue would probably extend a considerable distance downwind.

### Oil Content

The last two sets of data in Table 3 indicate the cumulative residues for two tests (C and D) in June 1966. The tests provide a direct comparison of residues from an application with a 2.8 percent O/W emulsion, test C, and an application with 100 percent diesel oil, test D. Both tests were under similar atmospheric conditions, S.R. 0.08 to 0.11. At 1/4 mile the residues with a 99 percent c.l. were 2.9 times as great from the diesel-oil application as from the 2.8 percent O/W application. Table 3 also shows that the residues (99 percent c.l.) were below 0.5 ppm at 1/4 mile for the 2.8 percent emulsion application, and that the diesel-oil application required approximately a 1/2-mile distance before the residue was less than 0.5 ppm. Line 3 in Fig. 7 illustrates the trend of the cumulative residues from the diesel-oil application. As shown, the residues remain at an exceptionally high level for the first 1000 ft, then drops very rapidly and at a distance of about 4600 ft approaches nearly the same residues as the lower-oil-content applications.

## SUMMARY

Results of 11 drift tests during 1966 were analyzed and discussed. The tests provided important information on the effect on drift residue characteristics of the following range of parameters: (a) micrometeorological conditions: wind velocity, 4.2 to 16 mph; temperature gradient, 0 F to a 3.9 F (temperature inversion); S.R., 0.0 to 3.9; (b) atomization: D6-46 nozzles at 5 to 7 gal per acre and D6-45 nozzles at 3 to 4 gal per acre; and (c) oil content: 100 percent oil and 2.8 percent O/W emulsion.

The following criteria for minimizing hazards of drift from aerial applications were identified:

### Micrometeorological Conditions

The Stability Ratio continued to serve as an important index of atmospheric conditions related to drift residues. The following table indicates four categories of atmospheric stability and the associated trend in drift residues:

| | S.R. | Residues at 1/4 mile |
|---|---|---|
| Unstable | -1.7 to 0.1 | lowest |
| Neutral | -0.1 to 0.1 | |
| Stable | 0.1 to 1.2 | |
| Very stable | 1.2 to 4.9 | highest |

At 1/4 mile the residues were over 13 times as much during a very stable condition as during neutral conditions. Thus, to minimize drift residues, applicators should avoid spraying during very stable atmospheric conditions generally found during strong temperature inversions accompanied with low wind velocities. High wind velocities generally produced nearly neutral stability, and additionally reduced the residue concentration by dilution or spreading the material over a greater distance.

### Atomization

Applications with D6-45 nozzles directed down produced residues 1/2 mile downwind that were 5.5 times as great as produced by a larger drop size spectrum from D6-46 nozzles directed back.

### Oil Content

The 100 percent-oil application produced over four times as much residue as the 2.8 percent O/W emulsion from 500 to 1000 ft downwind, and about equal residues at 4600 ft.

### Pesticide Residues

Table 3 lists estimated pesticide residues in ppm at various distances downwind in a variety of simulated field applications. The residue values based upon the upper 99 percent confidence limit can be used as a basic guide to establish safe operating conditions for specific chemical tolerances on nearby crops.

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# TWO MODELS OF LONG-RANGE DRIFT OF FOREST PESTICIDE AERIAL SPRAY

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**Abstract** – Long-range drift and dry deposition of an aerial insecticide spray onto a forest are calculated from gradient transfer and Markov chain models to 80 km downwind of the spray line. Horizontal homogeneity and neutral stratification with a capping inversion are assumed. The spray droplets are seven-eighths water which evaporates and one-eighth non-volatile Fenitrothion; the initial drop-size distribution is highly polydispersed with mass mean diameter ~82 μm.

Results show that at 80 km the models agree within a factor of 2.3 on the fraction of Fenitrothion still airborne (~0.2%), to within a few per cent on the mode of the spectrum of surviving droplets, ~22 μm, and substantially on the largest surviving droplet, ~40 μm. Results are shown to be sensitive to the assumed source configuration, the initial droplet spectrum and the droplet evaporative behaviour.

## 1. INTRODUCTION

Pesticide spraying operations to reduce the impacts of the Spruce Budworm moth on the forests of New Brunswick have been conducted for nearly 30 years. Such spraying is designed to kill the larvae in the immediate spray area. Recently concern has grown that an important fraction of the toxic spray escapes the target forest area and drifts considerable distances to impact very different environments.

This paper presents results from two models for such long-range drift and deposition of the aerosol cloud to the forest canopy. The two models are gradient transfer finite difference and Lagrangian Markov chain formulations. The gradient transfer theory for near ground releases has been shown by Lamb *et al.* (1975) to yield results for the mean concentration field in reasonable agreement with a Lagrangian model using the numerically simulated turbulent velocity field from the planetary boundary layer model of Deardorff (1970). In a series of controlled field experiments Crabbe (1976) also demonstrated good agreement between the prediction of a gradient transfer model and aircraft gas-chromatograph measurements of vertical diffusion of a tracer gas out to 30 km.

In order to focus the comparison a spray scenario was formulated. Scenario computations help quantify the extent of the drift, but more importantly, identify areas of poor understanding which cause important errors in assessments. The scenario is presented in the following section. In the next two sections the physical basis and computational procedures for both models are described. Results are presented for the airborne mass budget and lower surface deposition for both individual droplet diameter classes and the total mass of spray to a distance of 80 km downwind. The influences of various important input parameters are discussed.

## 2. THE SCENARIO

An area with negligible topographic variability is assumed to be covered by spruce forest with a tree height of 12 m. They are assumed uniformly spaced to yield a displacement height 90% of tree height. The atmosphere is assumed neutrally stratified from the surface to 400 m above ground where there is a capping inversion. The mean horizontal wind is assumed steady in direction and varying logarithmically in the vertical with friction velocity 30 cm $s^{-1}$ ($k$ = 0.35) and roughness length 1 m. This gives a wind speed of ~5 m $s^{-1}$ at inversion base. For the purposes of droplet evaporation computations, an ambient temperature of 10°C and relative humidity of 65% are used.

Aerial spraying is assumed to take place by three TBM tankers, flying along a line normal to the wind each with 600 U.S. gallons (2271 l) spray capacity. Composition of the spray is, by volume: 11% Fenitrothion pesticide, 1.5% Dowanal solvent, 1.5% Atlox emulsifer and 86% water. Fenitrothion and Atlox are found not to evaporate perceptibly over periods of a few hours of interest here, so the vapour pressure for spray evaporation is taken to be that for pure water down to 12.5% of the original volume (half the original dia.). No evaporation is assumed to take place thereaf-

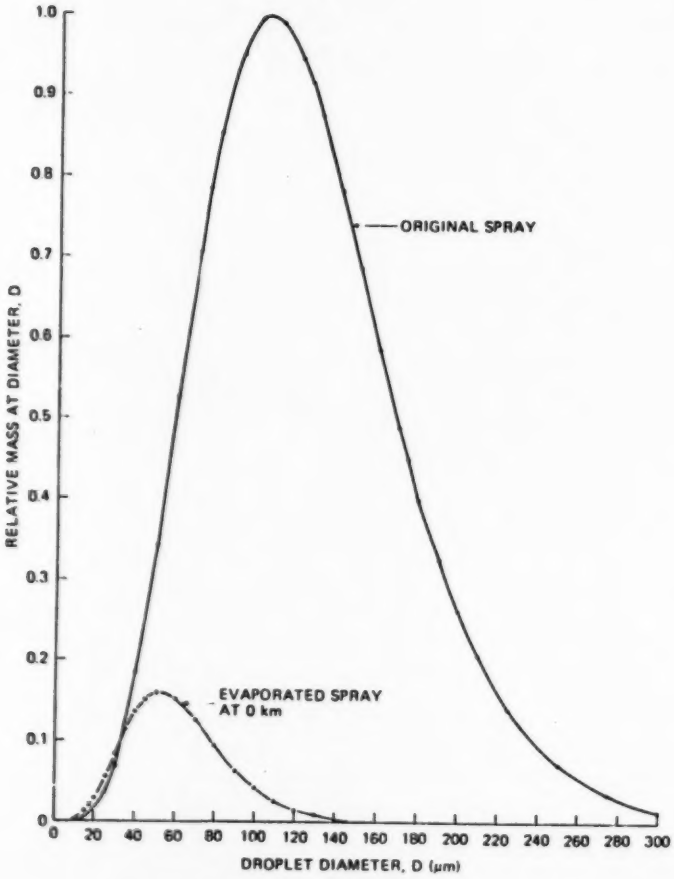


Fig. 1. Original and evaporated spray mass distributions.

ter. Droplets initially produced are assumed to have an incomplete gamma function distribution with a mass mean dia. of 82 μm. The mass distribution is shown in Fig. 1. Density of Fenitrothion component is 1.33 g $cm^{-3}$.

Finally, because of its structure each model makes somewhat different assumptions about the effective spray release height and surface deposition. Treated fully these are both very complex matters. The original scenario specification for release configuration was that spray is initially within a disc, representing aircraft wake, 12.2 m in dia with its lower edge at tree-top level. For deposition there was no specification except that the treatment be as realistic as possible.

## 3. THE GRADIENT TRANSFER MODEL

### *Formulation*

The conservation equation for the ensemble mean cross-wind integrated concentration $\chi$ is

$$\frac{\partial \chi}{\partial t} = -u\frac{\partial \chi}{\partial x} + \frac{\partial}{\partial z}\left(K\frac{\partial \chi}{\partial z} + w_s\chi\right). \qquad (1)$$

Here, vertical transport is specified by an eddy diffusivity but longitudinal diffusion is omitted as it is usually much smaller than stretching due to the interaction of vertical mixing with wind shear. The mean wind speed, $u$, has the logarithmic form

$$u(z) = \frac{u_*}{k}\ln\left(1 + \frac{z}{z_0}\right) \qquad (2)$$

for neutral stratification with $u_*$ the friction velocity, $k$ von Karman's constant, $z$ height above displacement height and $z_0$ roughness length. Mukammal (personal communication) indicates that wind profiles measured over forests do not tend to show the regularity of profiles over grassy surfaces, probably due to surface inhomogeneities. Measurements by Garratt (1978) support deviations from the logarithmic form in the lowest 50 m, but there is no widely accepted systemization.

Vertical eddy diffusivity is given by

$$K(z) = 1.35\,k u_* z\left(1 - \frac{z}{h}\right)^{1.5} \Big/ \left(1 + \frac{\beta^2 w_*^2}{\sigma_w^2}\right)^{1/2}, \qquad (3)$$

adapted from the work of Brost and Wyngaard (1978). The scaling height $h$ is the depth of the mixed layer from the displacement height to inversion base. The multiplicative factor 1.35 is taken from Businger *et al.* (1971), assuming that the eddy diffusivity for heat is appropriate for a passive contaminant. The square root quantity in (3) is Csanady's (1963) correction for the trajectory crossing effect experienced by a falling particle. In this term $\beta$ is the ratio of Lagrangian to

Eulerian integral time scales of turbulence assumed given by

$$\beta = 0.35\,u/\sigma_w, \tag{4}$$

where $u$ is the mean mixed layer wind speed, $w_s$ is the particle fall velocity and $\sigma_w$ the RMS turbulent vertical velocity.

Owing to the large roughness of the tree crowns, neither (3) nor, as suggested above, (2) is expected to be valid at tree-top level ($z = h_t$). In particular, both observation (e.g. Meroney, 1970) and calculation (e.g. Wilson and Shaw, 1977) show an inflection in the neutral wind profile at vegetation height implying that the eddy viscosity, $K_m \to u_*^2/(\partial u/\partial z)$, and hence the vertical eddy diffusivity have locally zero vertical gradient. To approximate this condition, the value of $K$ (uncorrected for the trajectory-crossing effect) in the first meter above tree-top height, i.e. up to approx two roughness lengths above the zero-plane displacement height, is assumed equal to its value from (3) at 1 m above the trees, 0.30 $m^2 s^{-1}$. A concomitant modification of the mean wind speed profile in this layer using the values of $u$ and $\partial u/\partial z$ at the top of the layer seemed an unnecessary refinement at this stage. Numerical results are given later which show that the deposition and hence the resulting cloud mass are relatively invariant to the assumed depth of this constant-$K$ layer.

The uncorrected value of $K$ at the upper boundary ($z = h$) was arbitrarily set to a low residual value of 0.2 $m^2 s^{-1}$ within 10 m of the inversion base. Although this value may be questioned, it is not expected to affect the deposition at the lower boundary.

$w_s$ in (1) and (3) is droplet sedimentation velocity and in the gradient transfer model is assumed equal to its terminal velocity according to Stoke's Law

$$w_s = \frac{D^2 g}{18\nu}\left(\frac{\rho_d}{\rho_a} - 1\right). \tag{5}$$

$D$ is droplet diameter, $g$ the acceleration of gravity, $\nu$ the kinematic viscosity of air (0.141 $cm^2 s^{-1}$ at 10 C), $\rho_a$ the density of air ($1.274 \times 10^{-3}$ g $cm^{-3}$) and $\rho_d$ is the droplet density. Droplet density changes as the droplet evaporates according to

$$\rho_d = 1 + 0.125 \times 0.33\left(\frac{D_0}{D}\right)^3, \tag{6}$$

applicable for $1 < D_0/D < 2$ with $D_0$ the original droplet diameter. For droplets greater than 50 $\mu$m dia an approximate Reynolds number correction, after Templin (1974), was applied, to account for underestimation of drag by the Stokes flow approximation. This was formulated as

$$w_{s(corr)} = w_s/(1 + 0.004(D - 50)). \tag{7}$$

Some examples of settling velocities computed from (5), (6) and (7) are:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $D_0$ ($\mu$m) | 100 | 100 | 50 | 50 | 25 | 25 | 12.5 |
| $D$ ($\mu$m) | 100 | 50 | 50 | 25 | 25 | 12.5 | 12.5 |
| $w_s$ (cm $s^{-1}$) | 26.86 | 10.29 | 8.06 | 2.57 | 2.01 | 0.64 | 0.50 |

The effect of evaporation on droplet diameter is treated by the method of Goering *et al.* (1972). They give

$$\frac{dD}{dt} = -2\left(\frac{M_v}{M_m}\right)\left(\frac{D_v}{D}\right)\left(\frac{\rho_a}{\rho_d}\right)\left(\frac{\Delta p}{\rho_f}\right) \times (2 + 0.6\,Sc^{1/3}\,Re^{1/2}), \tag{8}$$

where:

- $M_v$ is the molecular weight of the diffusing water vapour from the drop, 18;
- $M_m$ is the mean molecular weight of gas mixture in the transfer path, 29;
- $D_v$ is the diffusivity of water vapour in air, 0.241 $cm^2 s^{-1}$;
- $\rho_a$ is air density, $1.247 \times 10^{-3}$ g $cm^{-3}$;
- $\rho_d$ is the density of the droplet, computed from (6);
- $\Delta p$ is the difference between the saturation vapour pressure at the surface of the droplet and the vapour pressure in the surrounding atmosphere;
- $\rho_f$ is atmospheric pressure, 1013.25 mb;
- Sc is the Schmidt number

$$= D_v/\nu; \tag{9}$$

Re is the Reynolds number

$$= w_s D/\nu. \tag{10}$$

A large number of factors, some of them quite poorly quantifiable, influence the $\Delta p$ term. For example:

(1) evaporation of a large spray mass raising the ambient relative humidity;
(2) cooling of the droplet caused by evaporation lowering the vapour pressure at droplet surface;
(3) increase in the concentration of Fenitrothion in the droplet with evaporation;
(4) curvature of droplet surface effects (almost certainly negligible for this problem).

As a major simplification $\Delta p$ is specified corresponding to pure water, ambient 65% relative humidity and 10 C temperature in the scenario.

Boundary conditions are applied so that at the inversion there is no vertical flux

$$K\frac{\partial \chi}{\partial z} + w_s\chi = 0, \tag{11}$$

and at tree-top level

$$K\frac{\partial \chi}{\partial z} + w_s\chi = (v_D + w_s)\chi. \tag{12}$$

A major simplification is again required in selecting a value for the deposition velocity, $v_D$. The measurements of Chamberlain (1967) and of Wesely *et al.* (1977) indicate that the deposition velocities of aerosol and momentum are about equal so that $v_D(z) = v_D(\text{mom}) \equiv u_*^2/u(z)$. For a spruce forest, Shinn (1971) has measured $u_*/u = 0.49$ at tree-top level which gives $v_D \simeq 0.5u_* = 15$ cm $s^{-1}$, the value provisionally adopted in this study even though it could be ~ 10% too high in terms of the value of $u_*/u$ from (2), 0.44. The sensitivity of the numerical results to the value of $v_D$ is shown in Section 5 to be significant. However its parameterization in terms of momentum flux has a considerable background of observational support. Thus, even though the overall trend of Wesely *et al.*'s data is $v_D \simeq 0.7\,v_D(\text{mom})$ there is considerable scatter in their data so that the assumption in this study of strict equality between the two is not unreasonable.

An alternative specification of $v_D$ from Schmel and Hodgson (1978) was not used since their method is based on wind-tunnel studies with "smooth" surfaces. Their data, which indicate that $v_D$ is somewhat size dependent, probably reflect the poor collection efficiency of large foliage elements to small droplets, a situation which permits their retention by the flow. In the present calculation, however, the assumption is made that all material transported by turbulence and sedimentation through the plane $z = h_t$ is deposited.

The initial condition for spray release was simplified to the specification of an initial uniform concentration within a grid cell volume between 5 and 7 m above tree-top and from 0 to 410 m along the wind. This crudely accounts for what is very complex initial dispersion under the influence of aircraft vortex effects. A good detailed treatment of this early phase is given by Trayford and Welch (1977).

### *Solution*

Equation (1) was discretized to second order in finite differences and integrated numerically for concentrations at grid points using the Crank Nicolson algorithm. A coordinate transformation was applied to increase the resolution in the region of large concentration gradients. This gave a grid

the inversion at the end of a timestep it is moved an equivalent distance below and the sign of its turbulent velocity is reversed. This is a zero flux condition. At the lower forest boundary the formulation is quite different. As another major simplification any droplet or vapour molecule which moves below tree-top height is assumed deposited and withdrawn from further trajectory computations. This is in accord with the behaviour of large and moist particles, but as discussed earlier small particles and vapours tend to be not as efficiently deposited. Thus the perfect deposit efficiency assumed will tend to overestimate deposition of vapour and small droplets, but as these contain only a small proportion of the mass this is not likely to constitute a serious error.

*Solution*

Droplet trajectories are computed for small time steps under the influence of vertical turbulent motion, gravitational settling and horizontal wind with the assumption that each of these remains constant during one time-step. Time-steps of 20% of the Lagrangian time scale are adopted except near the surface where a lower limit of 1 s is established. Tests showed that results were not systematically influenced by this particular choice of time-step.

Separate computations were performed for representative droplet sizes across the spectrum of sizes for evaporated spray at 0 km (Fig. 1). Up to 10,000 initial droplets of any one size were followed. The number of droplets still airborne as a fraction of the total number released is computed at each 1/2 km distance from the source. Surface deposition is found from continuity. The downwind airborne mass fraction computed is plotted against diameter and interpolation used to derive values for intermediate diameters. By weighting with the mass in the original mass distribution spectrum (after evaporation) and using numerical integration the mass for the whole spectrum of droplet sizes is computed.

## 5. RESULTS

*Target area deposition*

Since the primary objective of the type of spraying operation being simulated is to kill the infestation in the immediate spray area, the initial deposition is of considerable interest. Computations of the percentage of Fenitrothion mass deposited in the first 500 m downwind from the spray line are shown below for individual droplet evaporated diameters and integrated over the total droplet spectrum.

| $D$, $\mu$m | 1 | 6.25 | 25 | 50 | 70 | 100 | Cumul. |
|---|---|---|---|---|---|---|---|
| GT | 29.8 | 30.0 | 45.2 | 80.2 | 97.9 | ~100 | 84.1 |
| MC | 43.6 | 45.6 | 53.8 | 77.3 | 92.5 | 99.2 | 82.2 |

The gradient transfer (GT) model predicts considerably less deposition for the smaller droplets in the first 500 m than the Monte Carlo (MC) calculation. The percent deposition increases for larger droplets with the MC' deposition becoming smaller than the GT for droplets larger than ~ 35 $\mu$m diameter. As most of the mass of droplets is in the intermediate diameter range (30 100 $\mu$m), away from the small diameter region showing large discrepancies, there is quite fair agreement between the cumulative percentage depositions, 84% for the GT as against 82% for the MC'.

The most important factor contributing to the discrepancy would seem to be the along-wind dimension of the initial cloud assumed in the GT model. The MC model assumed a point source at 6 m and the GT model a 2 × 410 m cloud between 5 and 7 m above the trees. Computations with the GT model for a steady point source of evaporated droplets at 6 m are compared below to GT cloud model predictions for the per cent deposit in the first 500 m downwind. Note that the steady point source GT model suffices for the budget figures reported in this paper, but the more detailed cloud source GT model was needed for other aspects of the scenario study not reported here.

| $D$, $\mu$m | 1 | 6.25 | 25 | 50 | 70 | 100 |
|---|---|---|---|---|---|---|
| GT (cloud source) | 29.1 | 30.0 | 45.2 | 80.2 | 97.9 | ~100 |
| GT (point source) | 48.3 | 48.9 | 56.8 (56.6) | 84.6 (79.2) | 99.0 (93.0) | 100 |
| MC' (point source) | 43.6 | 45.6 | 53.8 | 77.3 | 94.5 | 99.2 |

The agreement between the GT and MC' model predictions for the point source suggests that most of the discrepancy noted earlier is due to the effect of the initial source configuration, i.e. cloud vs point.

The parenthesized numbers in the above table are predicted by the GT point source model when the trajectory-crossing correction is ignored as is done in the MC' model. As expected, the agreement improves especially for droplet diameters greater than 25 m. Pasquill (1974) argues for the inclusion of this effect in calculating the eddy diffusivity, but in his expression $\beta$ multiplies the ratio $W'_z/u$ rather than $W'_z/\sigma_w$ as in Csanady's expression. The calculated effect is therefore smaller in the ratio $u^2/\sigma_w^2$ ($\simeq 130$ in the present scenario) and except possibly for "large" droplets may be ignored. It should be noted that the $K$-profile in these GT computations was otherwise the same as given by (3) with $K = 0.30\,\mathrm{m^2\,s^{-1}}$ for two roughness lengths above $z = d$. Increasing the depth of this constant-$K$ layer to an improbable five roughness lengths (with $K = 0.67\,\mathrm{m^2\,s^{-1}}$, therefore) only increased the deposit of the elevated cloud of 25 $\mu$m droplets from 45 to 50% in the first 500 m so that any mild departure of the eddy diffusivity profile near the tree tops from that given by (3) will not influence the results already quoted. The agreement between the two models, with somewhat different effective diffusivity profiles, is further confirmation that results are rather insensitive to these details of the formulation.

*Downwind deposition*

Figure 2 shows the downwind variation of percentage of droplets remaining in the atmosphere for nominal 1, 25 and 50 $\mu$m evaporated diameter droplets. Deposition can be computed from the slopes of these curves. Both models show greater percentage depletion for larger drops and smaller downwind distances. Thus the MC' model results show that between 9.5 and 10 km downwind deposition of vapour (droplets with negligible terminal velocity) is ~ 10% of its value for the first 500 m, whereas for 50 $\mu$m diameter droplets it is only ~ 0.1%.

Except for larger droplet sizes near the spray source the MC model predicts lower airborne mass than the GT model. Ratio of the GT to MC predicted air-

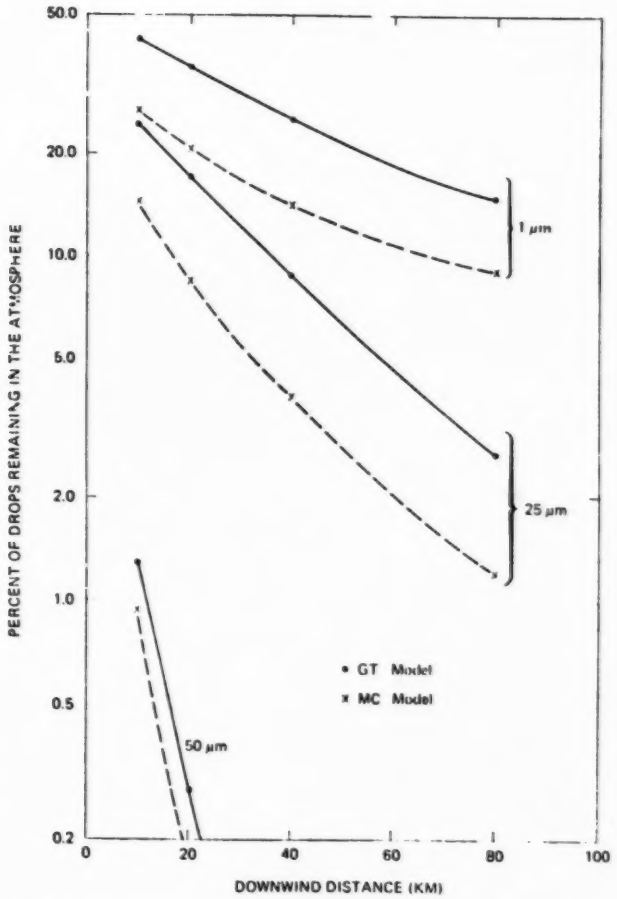


Fig. 2. Downwind variation of percentage of droplets remaining airborne for 1, 25 and 50 μm evaporated diameter droplets computed by the two models.

borne masses increases with downwind distance exceeding 2 for 25 μm droplets beyond 20 km. The continuity of the ratio trend suggests that it is a result of the difference in treatment of deposition to the surface. To examine this further the fractional depletion of airborne mass was computed based on masses airborne at 40 and 80 km, and exponential depletion

$$A = A_0 \exp(-\lambda x). \tag{20}$$

As is evident in the semi-logarithmic plot of Fig. 2, Equation (20) is not a good fit for all downwind distances, but does give a reasonable approximation over this limited downwind range. Derived $\lambda$s for various droplet diameters are shown in Fig. 3. Clearly $\lambda$s for MC calculations (crosses) are somewhat less than those from the GT model. Again both models show increasing depletion for larger droplets.

Also shown in Fig. 3 is a solid line indicating the $\lambda$ that would be expected for depletion due to sedimentation (according to Equations (17) (19)) from a layer uniformly mixed in the vertical. This simple assumption gives

$$\lambda = w_s/H\bar{U}, \tag{21}$$

where $w_s$ is sedimentation velocity, $H$ is inversion height (mixed layer depth) and $\bar{U}$ is mean mixed layer wind velocity (4.3 m s$^{-1}$ in this case). For droplets with no appreciable terminal velocity the GT and MC models predict $\lambda \simeq 1.2 \times 10^{-2}$ km$^{-1}$. This is the effect of turbulence and is equivalent to a $w_s$ of 2 cm s$^{-1}$ in (21). Droplets larger than ~ 20 μm show increasing differences between $\lambda$s computed by the two complex models and Equation (21). This reflects the tendency for larger droplets to be not as well mixed in the vertical as their smaller counterparts, decreasing the effective $H$ and $\bar{U}$ and so increasing $\lambda$.

*Situation at 80 km*

The GT model has 14.7% of the 1 μm droplets, 13.4% of the 6.25 μm droplets, 2.7% of the 25 μm droplets and essentially 0% of the 50 μm and larger droplets airborne at 80 km. This compares with 9.0% of the 1 μm droplets, 7.8% of the 6.25 μm droplets, 1.2% of the 25 μm droplets and 0% of 50 μm and larger

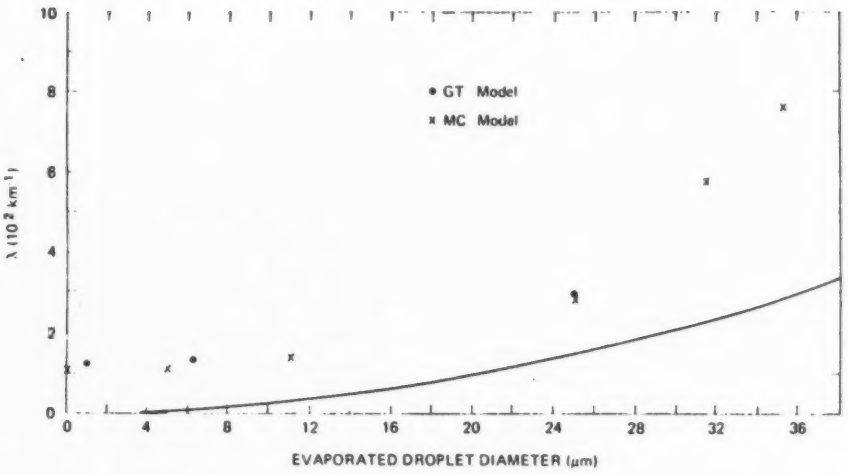


Fig. 3. Reciprocal decay distance ($\lambda$) as a function of droplet diameter for the two models. The solid line represents the depletion from a uniformly mixed layer resulting from sedimentation.

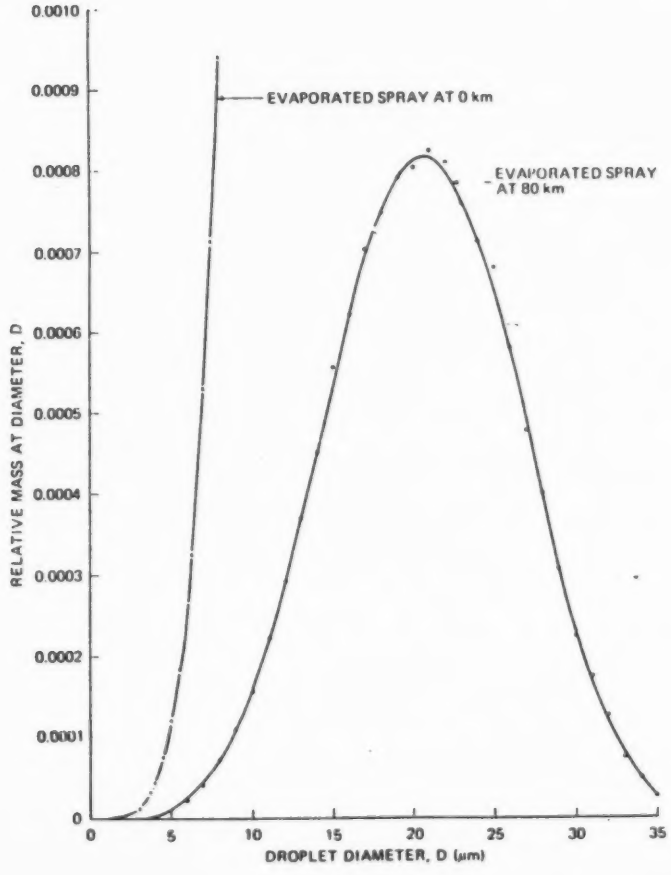


Fig. 4. The Monte Carlo model predicted mass distribution of airborne spray at 80 km.

droplets for the MC calculation. Integrated over the entire droplet spectrum the GT model predicts 0.27% of the original Fenitrothion mass is still airborne 80 km downwind. The equivalent value for the MC model is 0.12%. Figure 4 shows the MC model predicted mass distribution of spray droplets at this distance. The distribution appears fairly symmetrical with the mode diameter ~21 μm. The mass mean diameter was computed from the GT model as 23 μm. Both models predict essentially no droplets greater than 40 μm in the atmosphere by 80 km downwind. Of the original 1133 kg of Fenitrothion only 1 kg in 2.25 μm droplets and about 1/3 kg in 25 μm droplets remains in the atmosphere.

*Influence of input parameters*

The computations show the importance of a good knowledge of the spectrum of droplet sizes in the spray for long-range drift studies, in particular the droplets < 40 μm. These are also the sizes that would be of concern for respiration effects. The authors are informed that the initial gamma droplet spectrum used here was derived from droplet counts where only droplets > 30 μm could be counted, so that most of the spectrum of importance for long-range drift was based solely on extrapolation. Needless to say this is a far from satisfactory situation.

The effective source height above tree-top is also important. A calculation with the GT model showed that lowering the initial (evaporated) cloud base from 5 m to tree-top increased the deposit of 25 μm droplets in the first 500 m from 47% to 72%. A similar computation with the MC model lowering the point source height from 6 m gave an increase from 54% to 72% for a 2 m source height and 95% for a tree-top source height. Such large changes indicated the need for improved data on the effect of the spray aircrafts trailing vortices on the resultant height of the swath.

Droplet evaporation is a further critical factor for the airborne mass budget. The GT model examined a situation with 100% ambient relative humidity and found that 68% of the original formulation 50 μm droplets were deposited in the first 500 m compared to 45% deposition of the 25 μm evaporated spray droplets. A parallel calculation with the MC model showed an increase from 54% to 71%. In view of the suppression of evaporation by reduction of vapour pressure through cooling of the droplet to wet-bulb temperature, and by increase of background humidity from water already evaporated, the initial deposition without evaporation may be more realistic.

Equally important is the influence of the value assigned to the dry deposition velocity, $v_d$. Halving this from 15 to 7.5 cm s$^{-1}$ in the GT model reduced the deposit from 72 to 63% in the first 500 m for a cloud of 25 μm evaporated droplets initially at tree-top level. The same computation for the elevated point source changed the deposit of 25 μm droplets from 56.5% to 52.1% and of 1 μm droplets from 48.3 to 41.8%. When compared to the MC model prediction these results indicate that the model value $v_d$ = 15 cm s$^{-1}$ may be too high. However, beyond 40 km downwind where the source configuration is no longer important, the GT cloud model and the MC model are in remarkable agreement on the predicted deposition profile. How realistic these results are, however, for an actual aerial spray will probably only be determined by carefully acquired field data.

## 6. CONCLUSIONS

Advanced gradient transfer and Monte Carlo environmental assessment models have been applied to a forest insecticide spray scenario. Although the scenario specifies many aspects of the situation other aspects remain open to a reasonable diversity of interpretation. Thus model results differ depending on the nature of parameterizations and additional assumptions adopted. A comparison of results illustrates the differences arising and so the uncertainty that may be expected when, as is more common, only a single model assessment is pursued. As an example for the assessment of long-range drift, there is a factor of 2.3 between the model predicted airborne insecticide masses at 80 km downwind of spraying.

Model results were employed to investigate the nature of the differences and their causes. There was good qualitative agreement between the models for these sensitivity investigations. Since only spray droplets less than about 40 μm diameter survived in the atmosphere to 80 km, knowledge of the small diameter end of the spray mass distribution is critical. A good knowledge of the droplets' evaporative behaviour is also important. Knowledge of both these items proves to be significantly limiting for this application. In general larger droplets and slower evaporation serve to increase target area deposition and decrease long-distance drift.

The assumed initial source configuration, particularly source height, was significant for target area deposition, more so for smaller droplet diameters. A modified version of the GT model incorporating a point rather than cloud source configuration improved the agreement between the GT and MC model initial deposition estimates, and would reduce the discrepancy in airborne masses at 80 km to within a factor of 2. However, the effective source height approach used here is quite crude; improved studies of the interaction of aircraft vortices with an underlying forest canopy and of droplet trajectories within the vortices are urgently needed.

The near-field deposition of the smaller droplets is also sensitive to the value assigned to the dry deposition velocity in the GT model. Although current parameterization leads to equality of deposition rates for aerosol and momentum, comparison of the two model predictions in this paper would indicate the former could be somewhat less. Careful studies are needed to remove this uncertainty. On the other hand, the same comparison clearly de-emphasizes the impor-

tance of a trajectory-crossing correction to the eddy diffusivity for this problem.

Overall, the two models, although structured quite differently and employing grossly different source configurations, show 'factor-of-two' agreement. This may be good enough for environmental assessment problems. The thrust should now be toward improving the realism of the input parameters, including spatial and temporal variation.

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